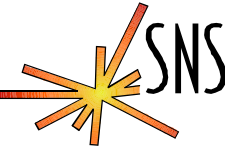


# SNS LLRF Reference System

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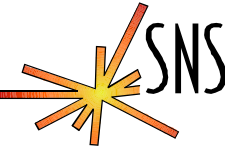
## SNS LLRF Reference System 402.5 MHz Section

Chip Piller  
January 30, 2003  
Oak Ridge National Laboratory



# SNS LLRF Reference System

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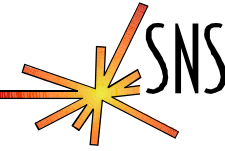
## README about this Document

- This file is [SNSref.26.sxi](#), created Feb 7, 2003
- This document was created using OpenOffice.org, a free and open source office program available for several platforms at <http://www.openoffice.org>.
- Exporting this document to other formats may result in loss of information if the other file format is not open and documented.
- Please send any feedback, corrections, or suggestions to Chip Piller, email: [piller@sns.gov](mailto:piller@sns.gov)



# SNS LLRF Reference System

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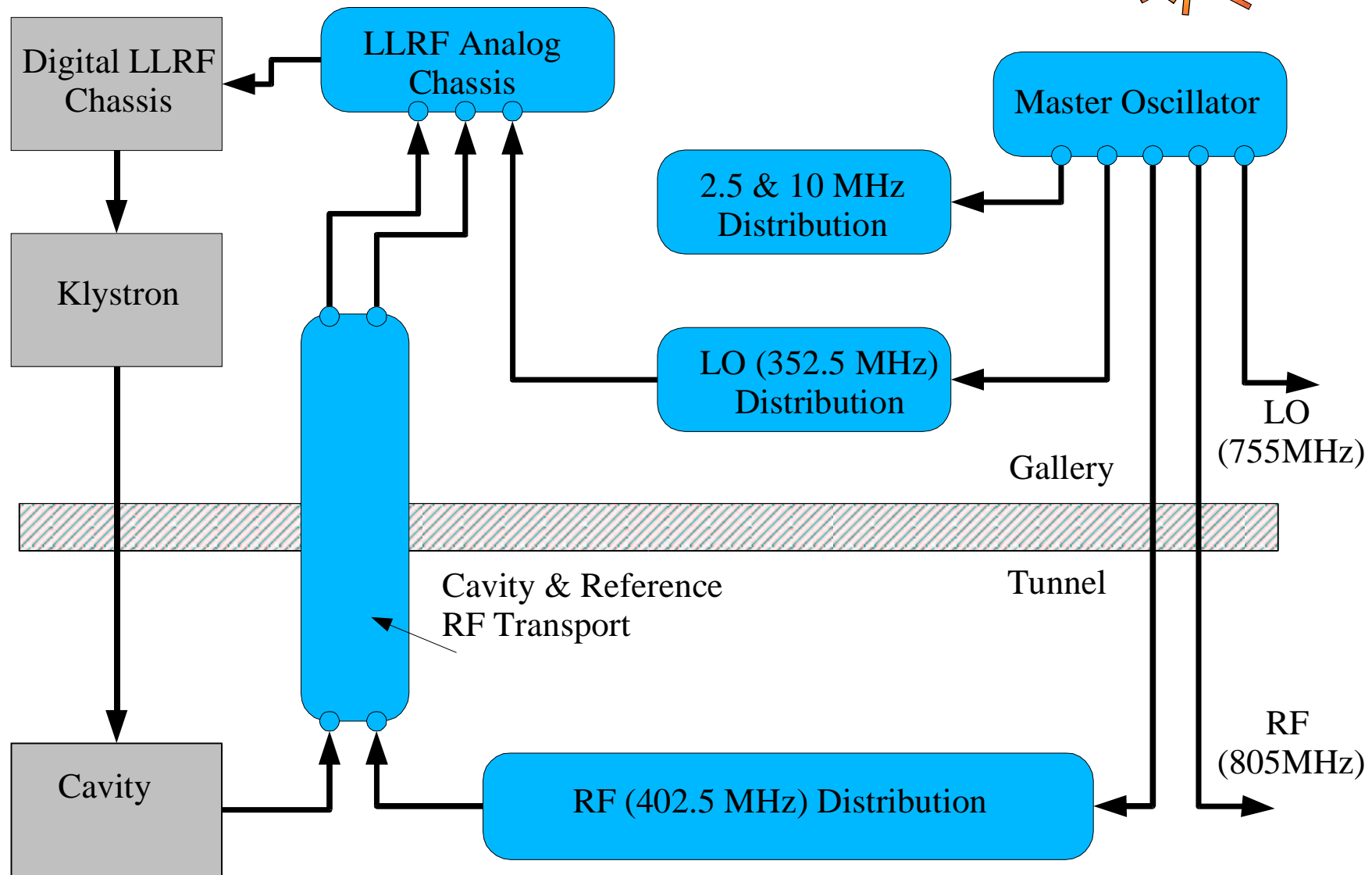
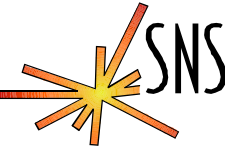


## Outline

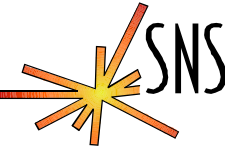
- What is the SNS LLRF Reference System?
- Specifications and Requirements
- What we plan to build (402.5 MHz section)
- Why it will work
- When we will build it
- Future Plans
- Acknowledgement



# SNS LLRF Reference System



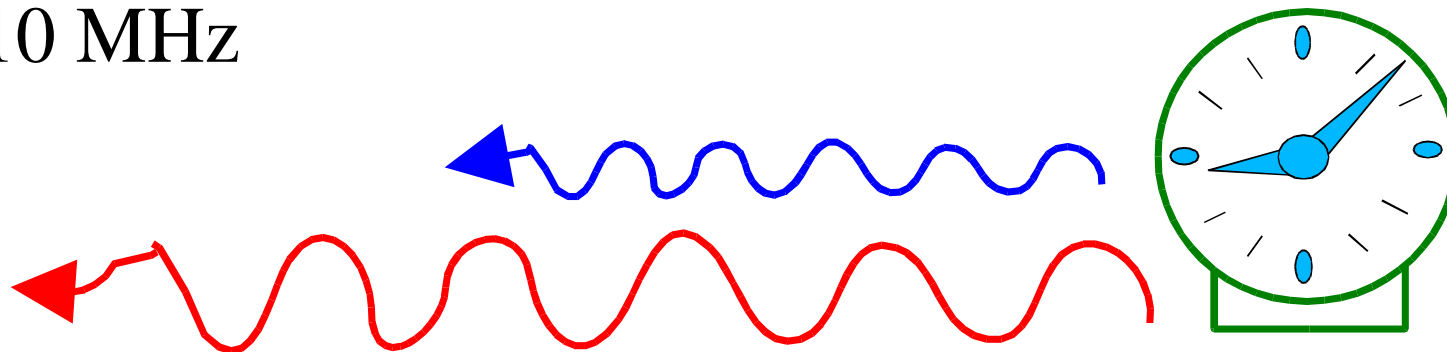
# SNS LLRF Reference System



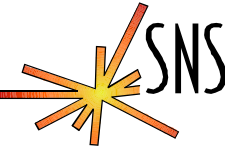
## What is the SNS LLRF Reference System (1 of 2)?

Distributes reference signals:

- 402.5 MHz RF (precise phase)
- 352.5 MHz LO signal
- 2.5 MHz common base
- 10 MHz

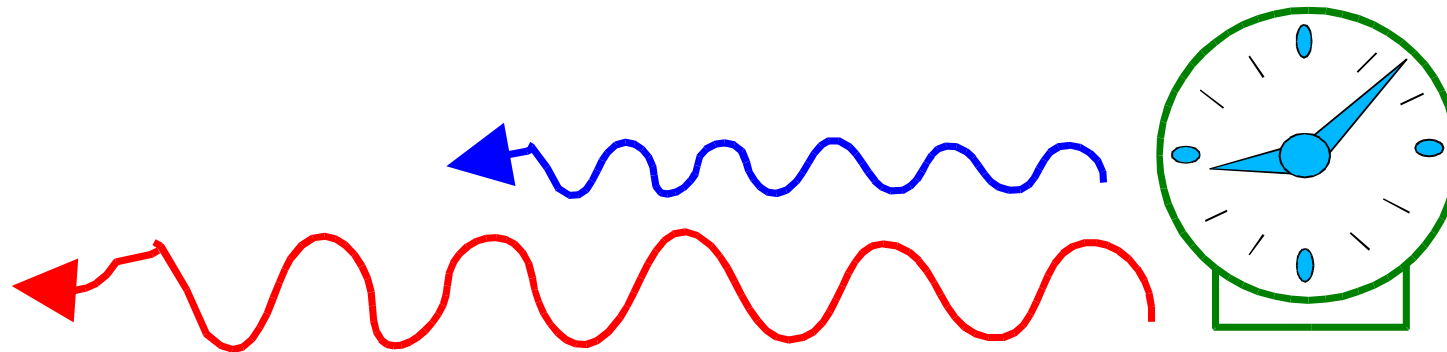


# SNS LLRF Reference System



## What is the SNS LLRF Reference System (2 of 2)?

- Down-converts Cavity RF and Reference RF signals (402.5 MHz) to Cavity IF and Reference IF signals (50 MHz)
- Handles REF, CAV, LO, IF, FWD, REV distribution at LLRF rack



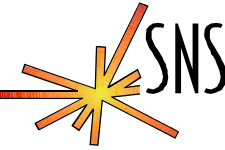
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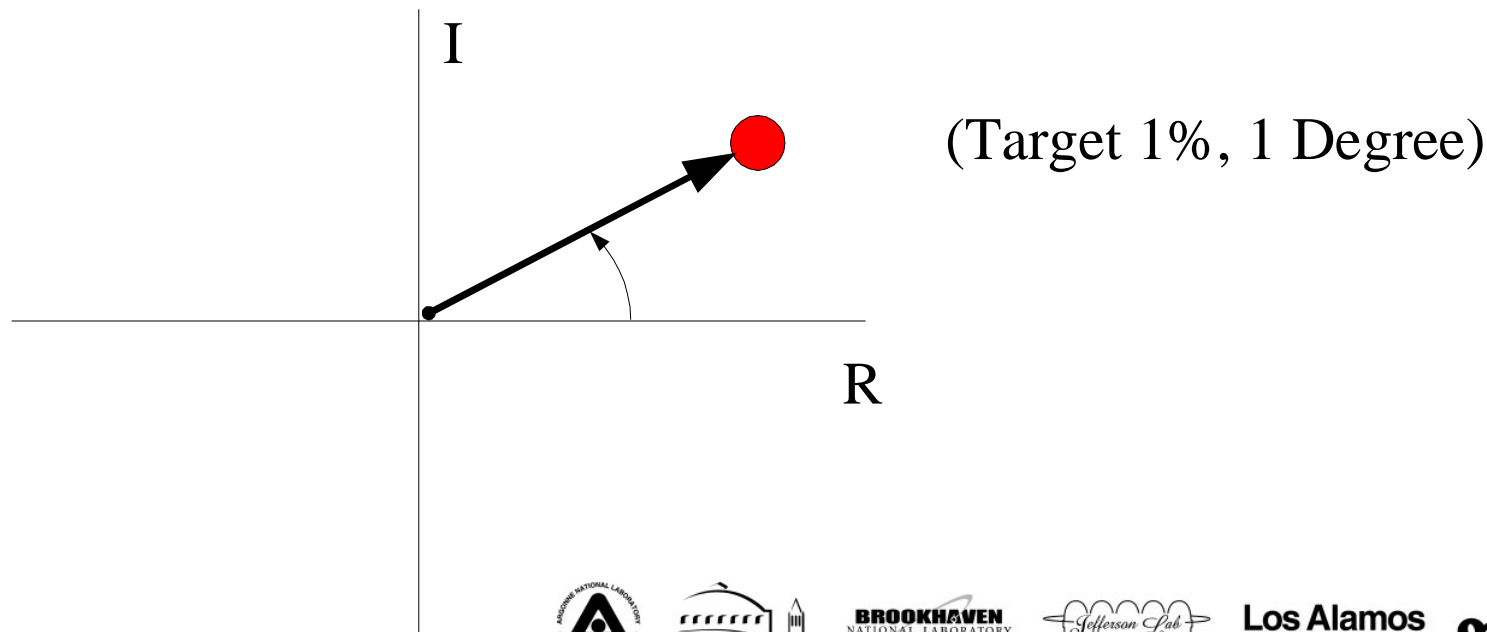
# SNS LLRF Reference System



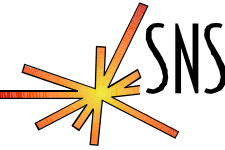
## LLRF Specifications (1 of 4)

### Cavity Field Control

- Amplitude  $\pm 1.0$  % Max Steady State
- Phase  $\pm 1.0$  degree Max Steady State



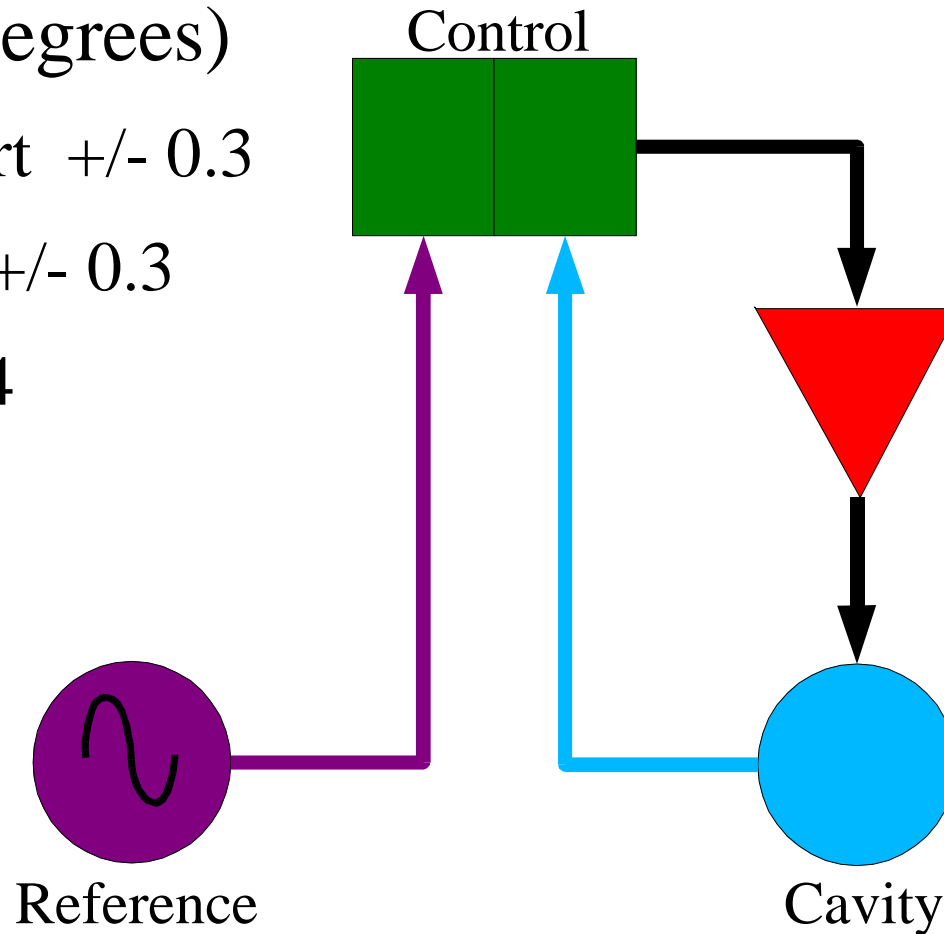
# SNS LLRF Reference System



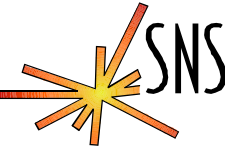
## LLRF Specifications (2 of 4)

### Phase Error Budget (degrees)

- Reference RF Transport  $\pm 0.3$
- Cavity RF Transport  $\pm 0.3$
- Control System  $\pm 0.4$
- Total  $\pm 1.0$

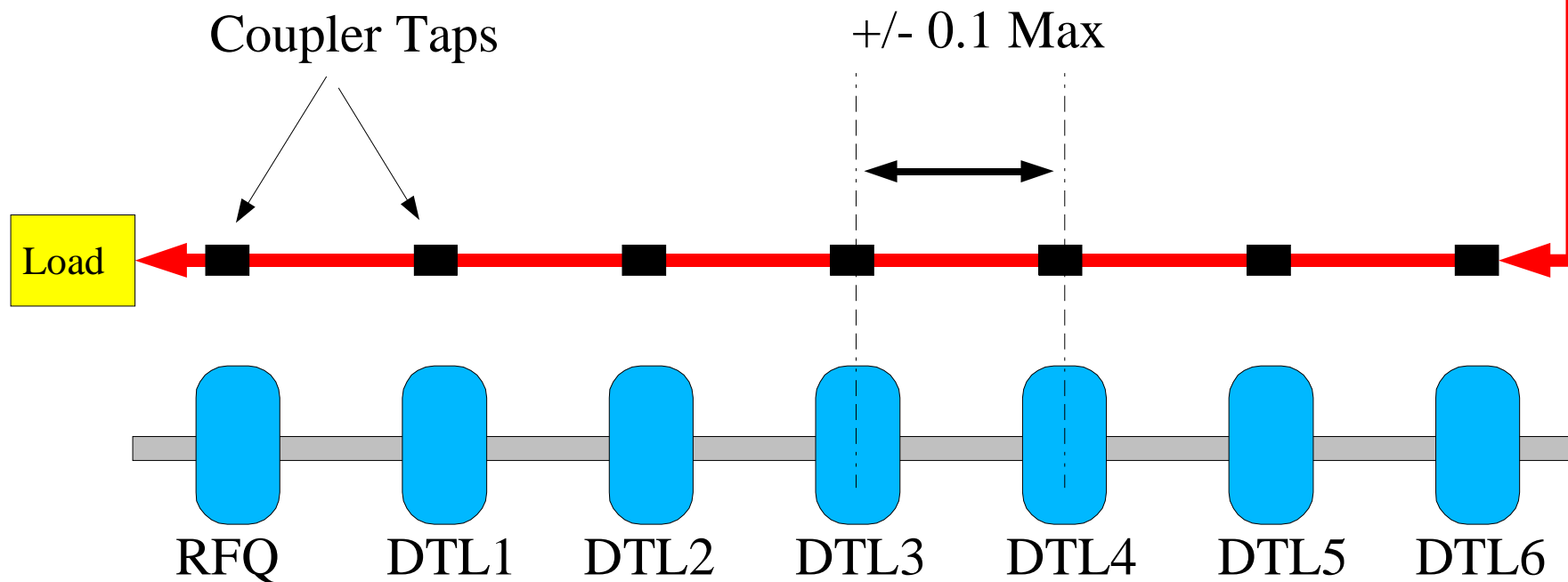
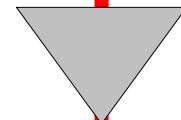
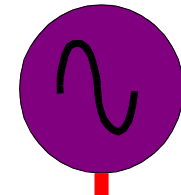


# SNS LLRF Reference System



## LLRF Specifications (3 of 4)

Phase Stability between adjacent cavities  $\pm 0.1$  degree Max, not to exceed  $\pm 2.0$  degrees between any two points in the linac



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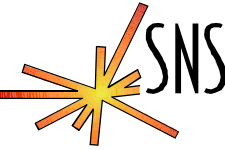


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# SNS LLRF Reference System

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## LLRF Specifications (4 of 4)

No Teflon is allowed in the tunnel!

- This makes things difficult, almost every RF component in tunnel needs to be custom made.



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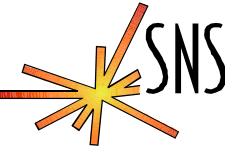


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# SNS LLRF Reference System

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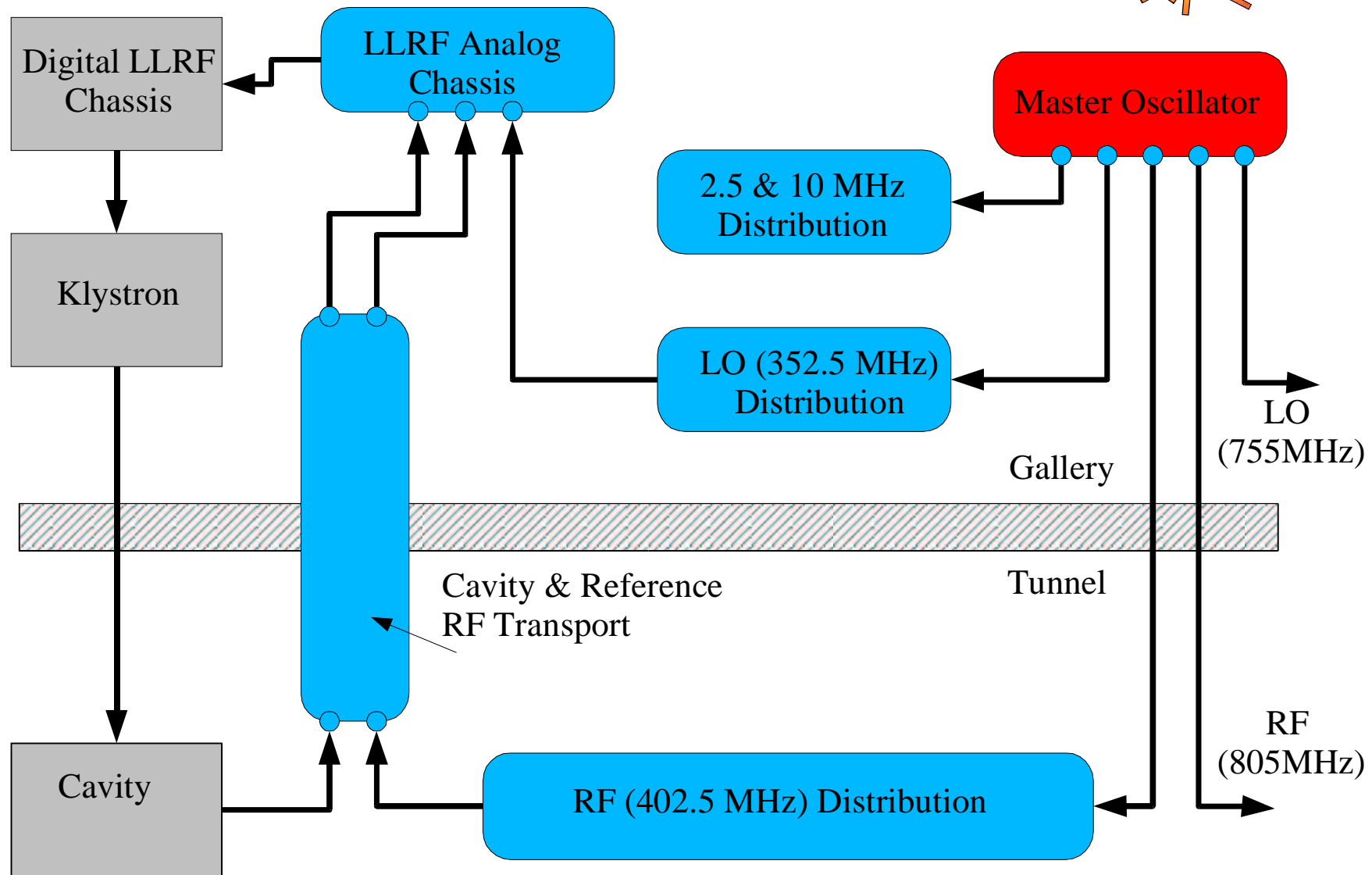
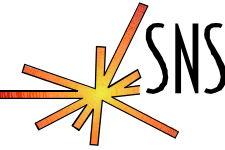


## 402.5 MHz System Design

- Master Oscillator
- Reference RF (402.5 MHz) Distribution
- Reference LO (352.5 MHz) Distribution
- Cavity RF and Reference RF Transport
- LLRF Analog Chassis
- 2.5 MHz & 10 MHz Distribution



# SNS LLRF Reference System



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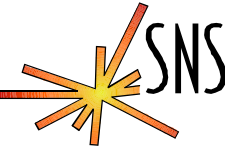


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# SNS LLRF Reference System

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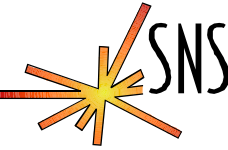
## Master Oscillator (1 of 3)

Produced by Wenzel Associates.

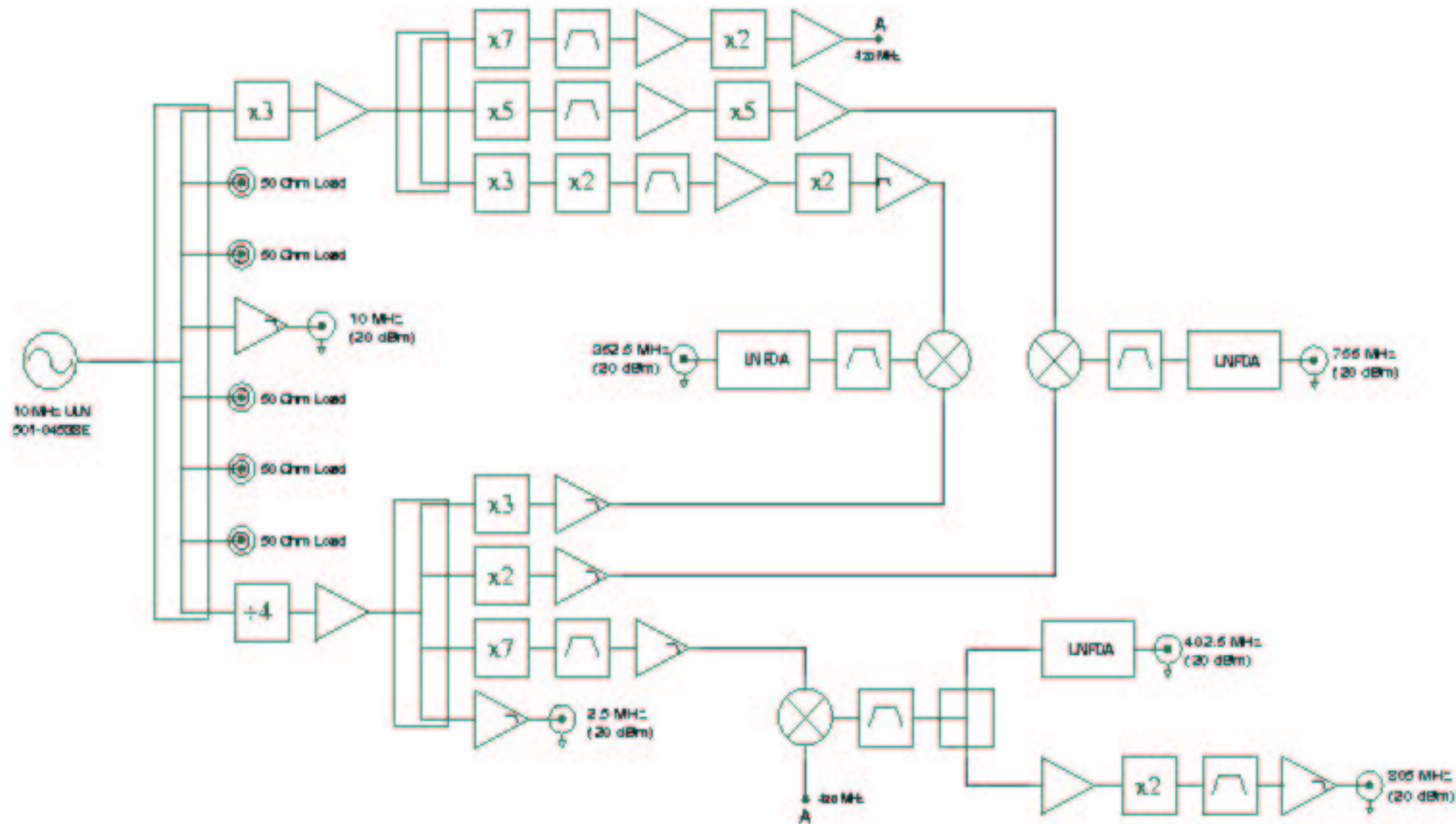
- Direct Analog Design
  - Produces Phase Coherent Output Signals
  - Low jitter, excellent close-in phase noise characteristics
- Rack mount chassis located in Master Oscillator Rack (Row7, Rack3) between DTL and CCL
- Type N-female connectors on rear of chassis



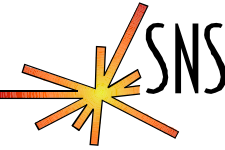
# SNS LLRF Reference System



## Master Oscillator (2 of 3)



# SNS LLRF Reference System



## Master Oscillator (3 of 3)

Internal Reference: Premium 10 MHz-SC ULN (501-04538E)

Output Frequencies (1 EA):

- 2.5 MHz, +20 dBm
- 10 MHz, +20 dBm
- 352.5 MHz, +20 dBm
- 402.5 MHz, +20 dBm
- 755 MHz, +20 dBm
- 805 MHz, +20 dBm

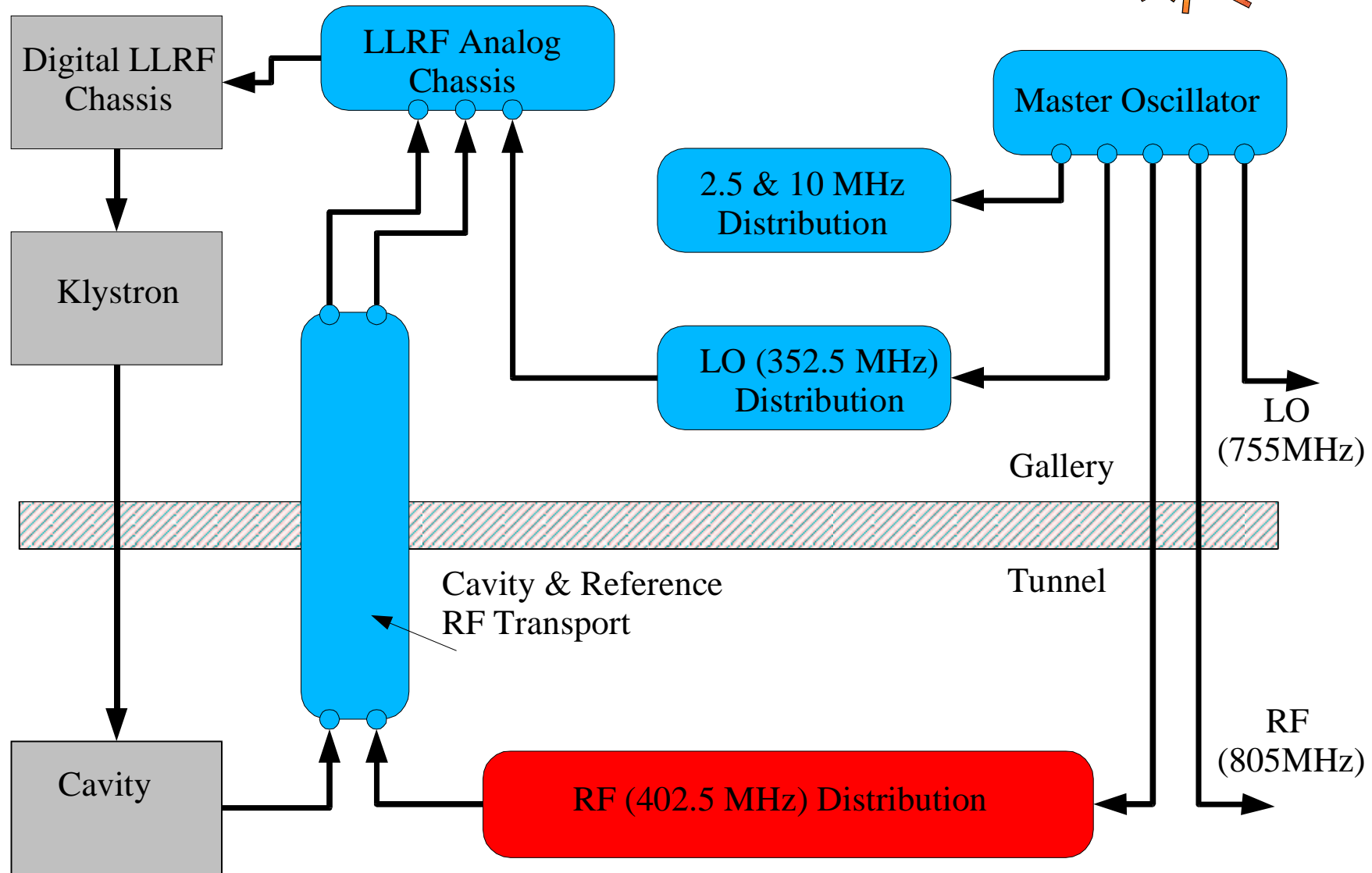
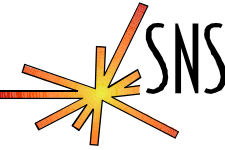
Phase Noise:	2.5 MHz	10 MHz	352.5 MHz	402.5 MHz	755 MHz	805 MHz
1 Hz	-117 dBc	-105 dBc	-74 dBc	-72 dBc	-67 dBc	-67 dBc
10 Hz	-144 dBc	-132 dBc	-101 dBc	-99 dBc	-94 dBc	-94 dBc
100 Hz	-154 dBc	-142 dBc	-111 dBc	-109 dBc	-104 dBc	-104 dBc
1 kHz	-155 dBc	-147 dBc	-118 dBc	-117 dBc	-114 dBc	-114 dBc
10 kHz	-155 dBc	-147 dBc	-118 dBc	-117 dBc	-114 dBc	-114 dBc

Harmonics: -40 dBc

Spurious: -80 dBc

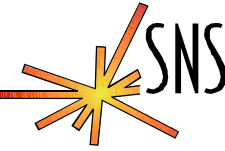


# SNS LLRF Reference System



# SNS LLRF Reference System

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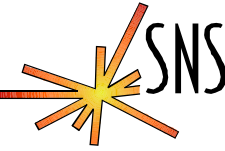
## Reference RF 402.5 MHz Distribution (1 of 12)

- Power Amplifier
- Feed Line
- Distribution Line in Tunnel
- Temperature Control System
- Pressure Control System



# SNS LLRF Reference System

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## Reference RF 402.5 MHz Distribution (2 of 12)

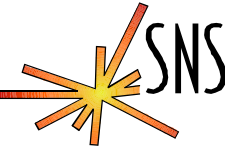
### Power Amplifier

- Rack mount chassis in Master Oscillator Rack
- Gain = 40 dB
- Noise Figure < 8.6 dB
- Typical Maximum Power Output = 50 Watts
- Minimum 1 dB Compression Point = 25 Watts



# SNS LLRF Reference System

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## Reference RF 402.5 MHz Distribution (3 of 12)

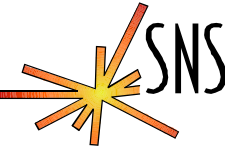
### Feed Line From Master Oscillator Rack to Tunnel

- 7/8" Heliax Cable ( $V_p=0.89$ , Loss=2.5 dB/100m)
- Length = 21m, Loss = 0.6 dB
- Wavelength = 66.3 cm @ 402.5 MHz
- Feed Line approximately 32 wavelengths long
- 7/8" EIA Flange connectors
- Temperature Regulation not required at present



# SNS LLRF Reference System

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## Reference RF 402.5 MHz Distribution (4 of 12)

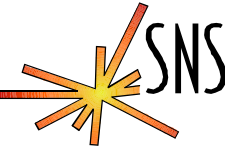
### Distribution Line In Tunnel

- Andrew Corporation 3-1/8" Copper Rigid Line
- Section lengths 20 feet (6.1 m)
- EIA flange connectors
- Propagation Velocity = 0.99 c
- Attenuation 0.65 dB/ 100m @ 402.5 MHz



# SNS LLRF Reference System

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## Reference RF 402.5 MHz Distribution (5 of 12)

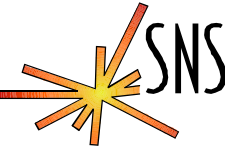
### Distribution Line In Tunnel

- Overall Length 140 feet (42.67 m)
- Main Line Loss = 0.3 dB
- Wavelength = 73.8 cm @ 402.5 MHz
- Rigid Line Length is  $42.67 \text{ m} / 73.8 \text{ cm} = 57.8$  Wavelengths
- No bellows or flex type joints



# SNS LLRF Reference System

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## Reference RF 402.5 MHz Distribution (6 of 12)

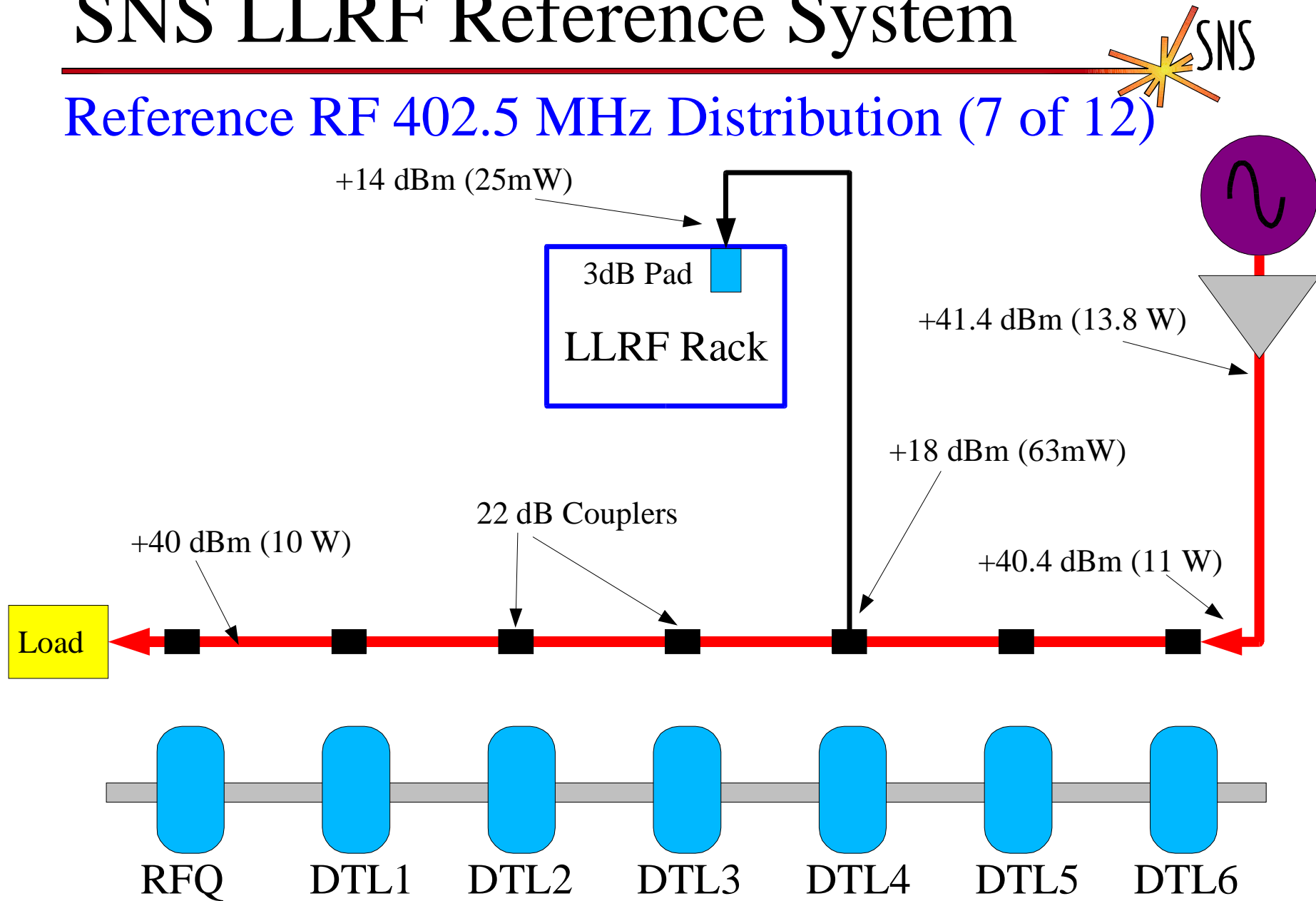
### Distribution Line

- Directional Couplers located every 10 feet (3.05 m), not all will be used.
- Coupling value = -22 dB
- Coupler Directivity = 21dB
- Type N-female Directional Coupler Connectors



# SNS LLRF Reference System

## Reference RF 402.5 MHz Distribution (7 of 12)



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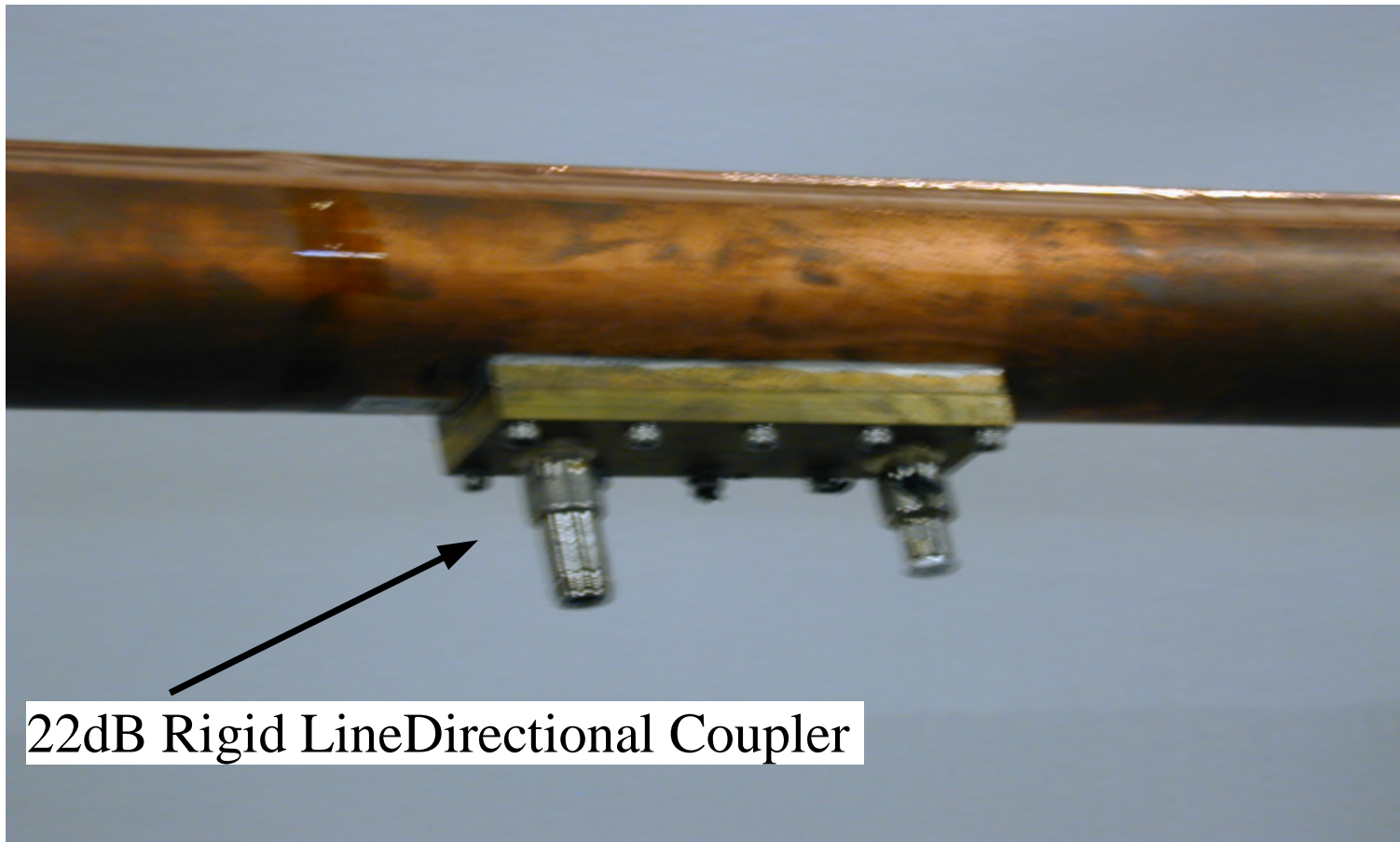
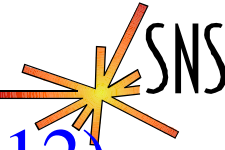


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# SNS LLRF Reference System

Reference RF 402.5 MHz Distribution (8 of 12)



22dB Rigid Line Directional Coupler



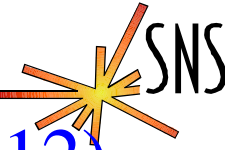
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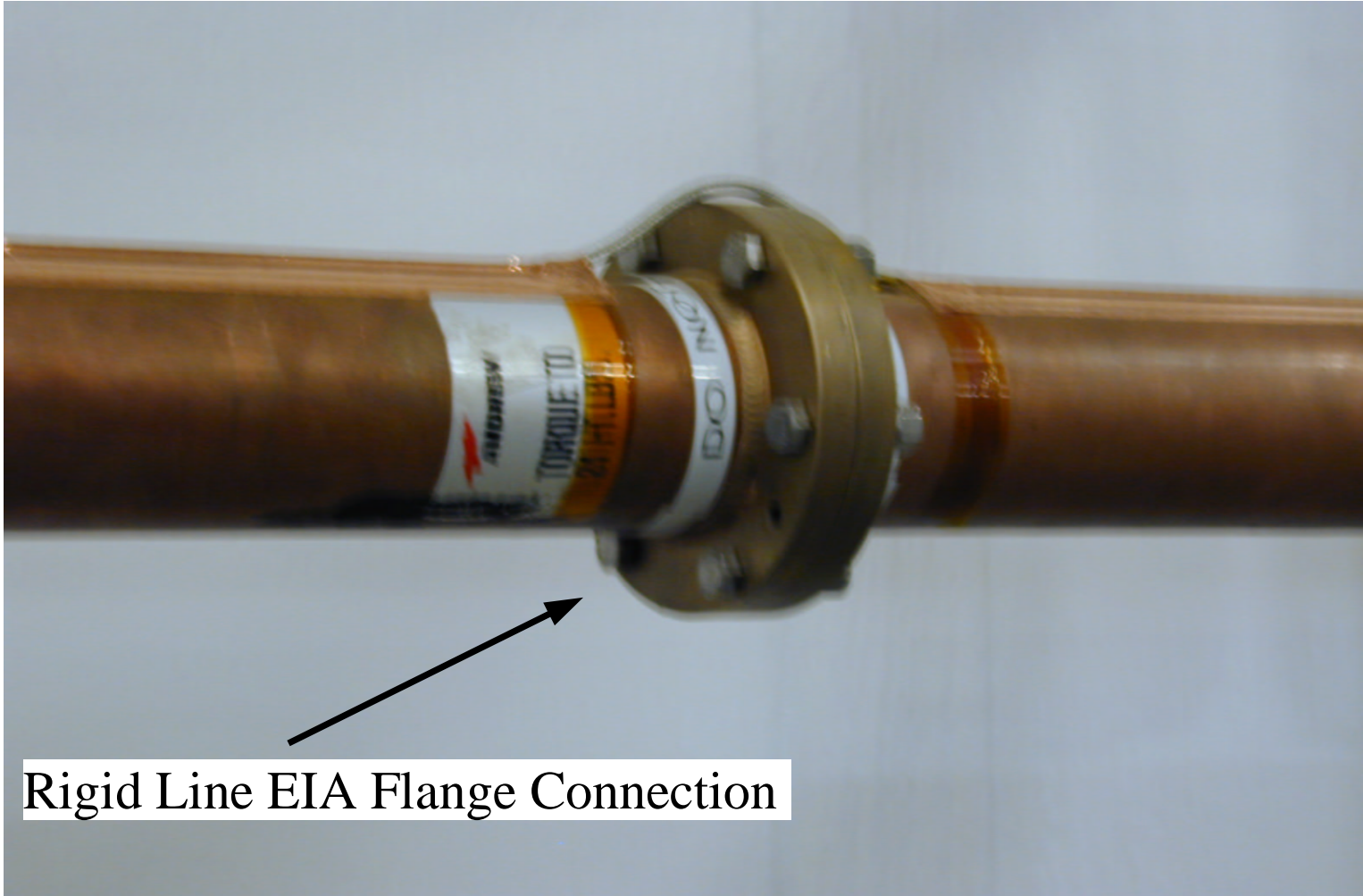
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# SNS LLRF Reference System



Reference RF 402.5 MHz Distribution (9 of 12)



Rigid Line EIA Flange Connection



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# SNS LLRF Reference System



Reference RF 402.5 MHz Distribution (10 of 12)



Roller Hanger Supports  
every 6 Feet.



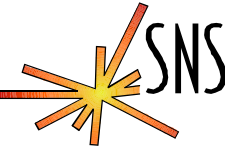
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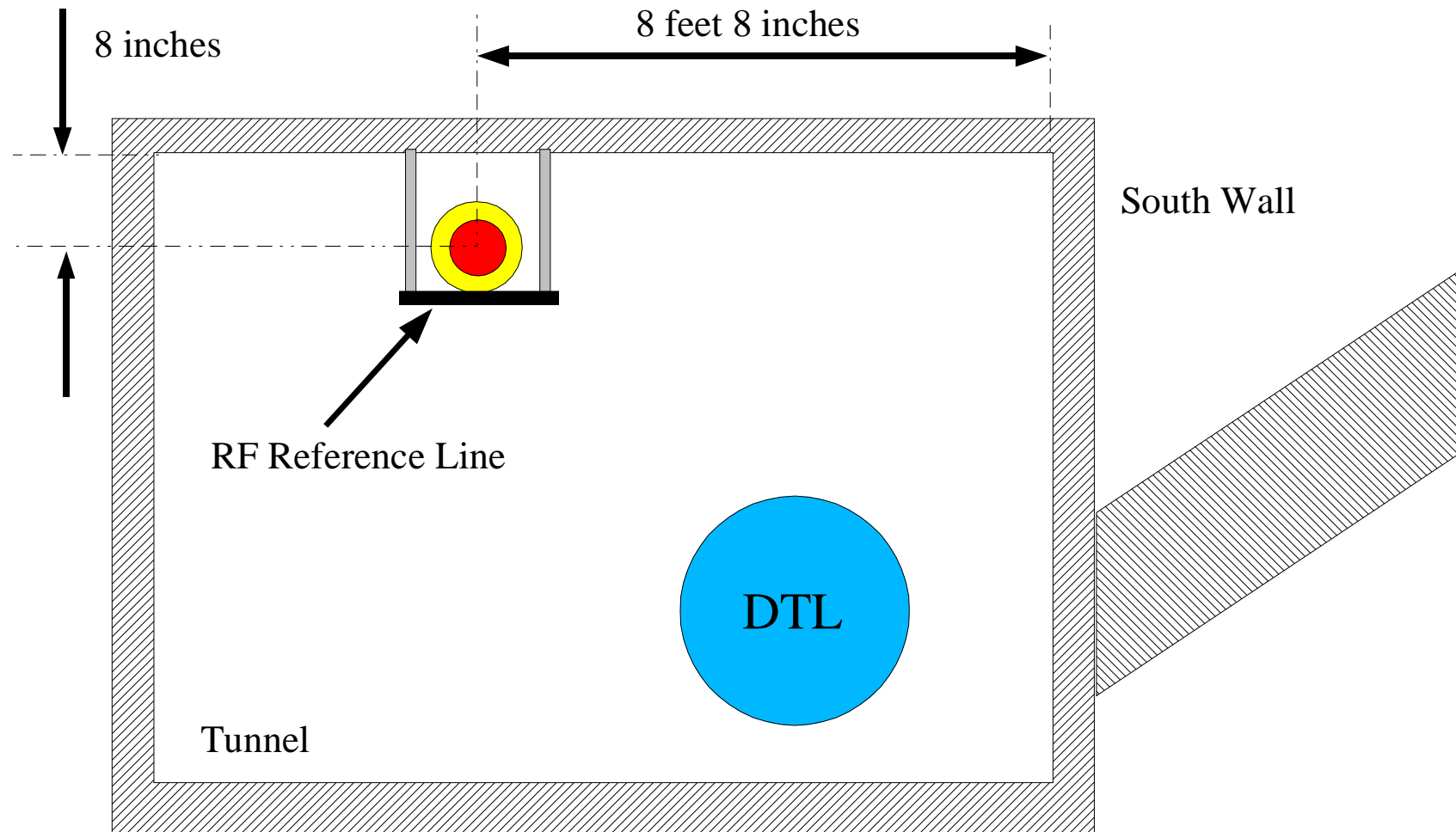
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# SNS LLRF Reference System



## Reference RF 402.5 MHz Distribution (11 of 12)



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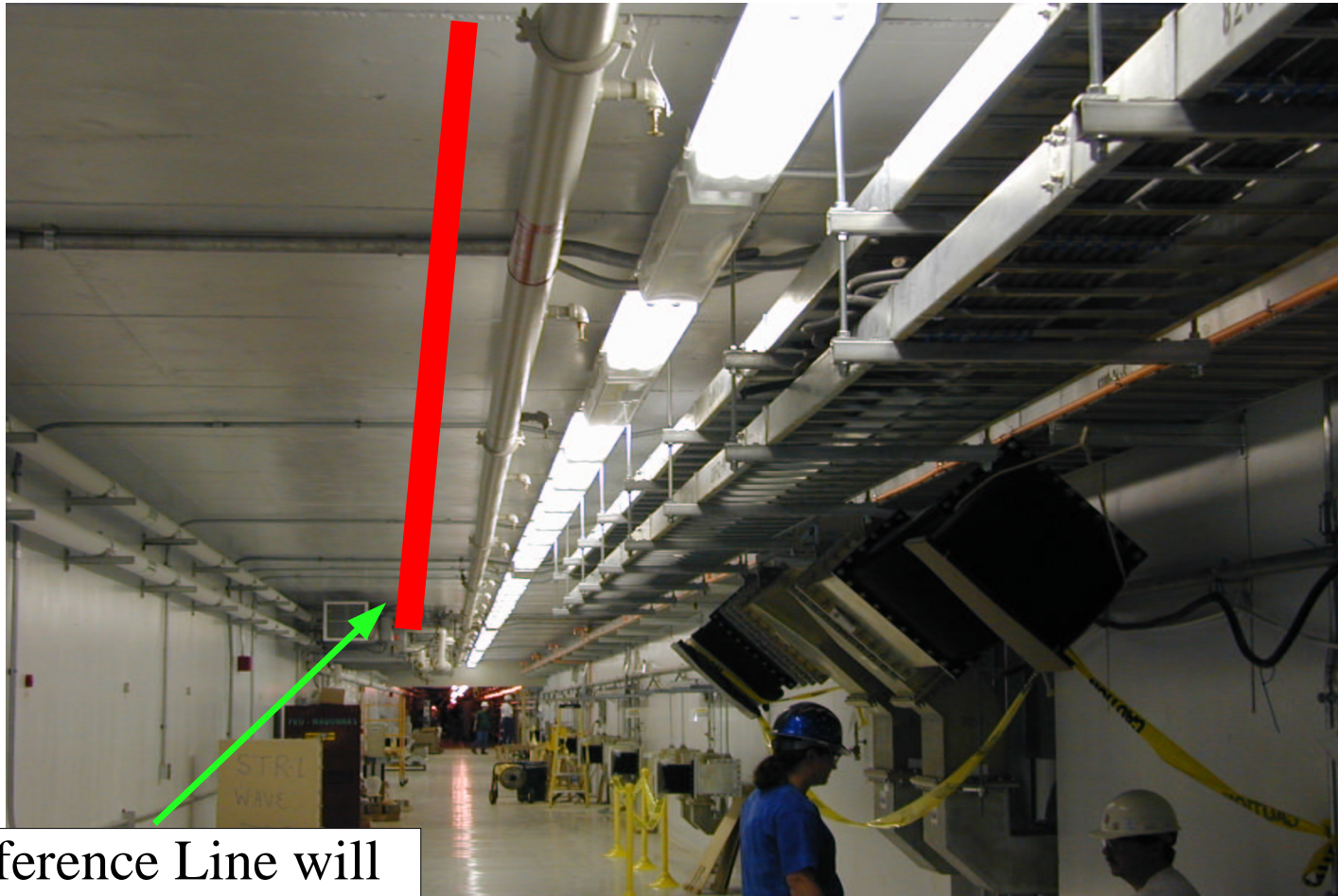
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# SNS LLRF Reference System



Reference RF 402.5 MHz Distribution (12 of 12)

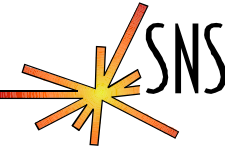


Reference Line will  
go here.



# SNS LLRF Reference System

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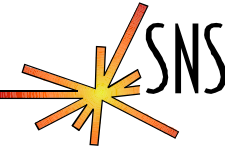
## Temperature Control System (1 of 4)

- Reference RF distribution line in tunnel is temperature regulated to  $\pm 0.1^\circ\text{C}$
- Two temperature controlled zones.
- Two 4 wire RTD temperature sensors per zone (one for active control, one as a monitor)
- Heat tape output is 8 W/ ft, tape applied to top and bottom of Rigid Line



# SNS LLRF Reference System

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## Temperature Control System (2 of 4)

- Heat tape applied with copper tape and Kapton tape
- Rigid Line insulated with commercial 1.5" thick fiberglass pipe insulation sections each 3 feet long
- Visual indicator installed at end of heat tape
- Overtemp protection



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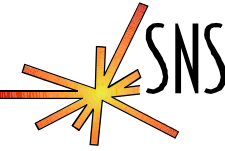


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# SNS LLRF Reference System

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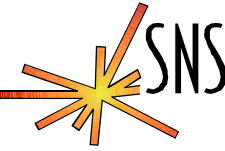


## Temperature Control System (3 of 4)

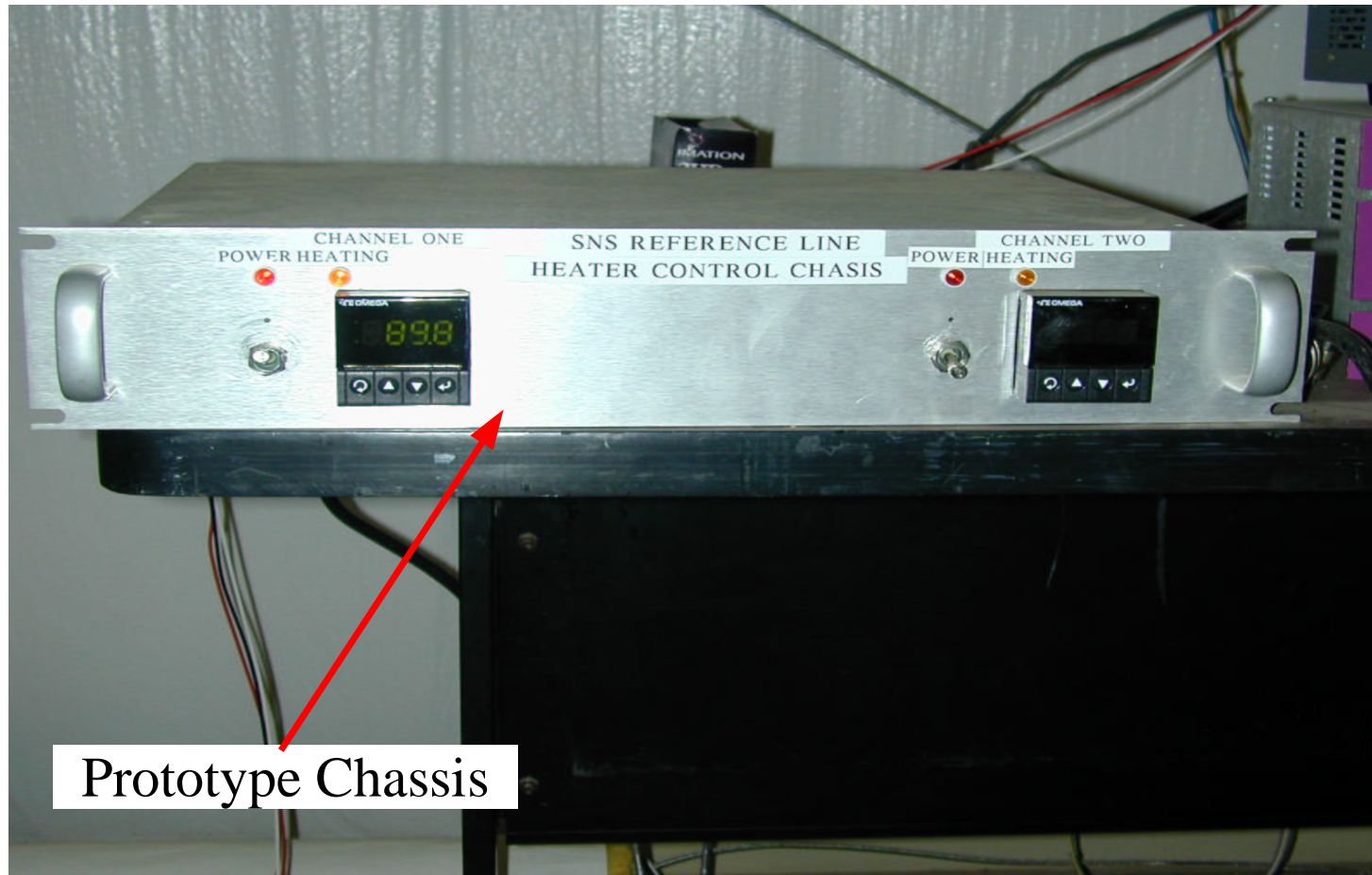
- Temperature Control Chassis located upstairs in RFC rack.
- Each chassis contains 2 Omega i-series PID Temperature/Process controllers with RS232/RS485 interface to Epics



# SNS LLRF Reference System



## Temperature Control System (4 of 4)

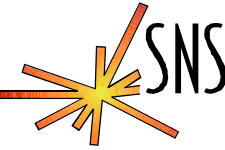


Prototype Chassis



# SNS LLRF Reference System

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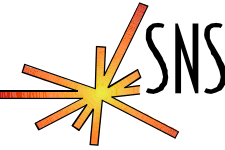
## Pressure Control System (1 of 3)

- Copper 3-1/8" Rigid Line has air dielectric
- NPT fittings located at ends of Rigid Line
- Presently Testing Andrew Corporation Dehydrator/Pressure control system (5 psi gauge)



# SNS LLRF Reference System

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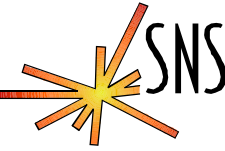


## Pressure Control System (2 of 3)

- Pressure System Chassis to be located in MAO or adjacent RFC rack.
- Pressure System Chassis will monitor pressure and interface with EPICS
- Two very high accuracy absolute pressure transducers and Omega DP41 series process controllers in Chassis



# SNS LLRF Reference System



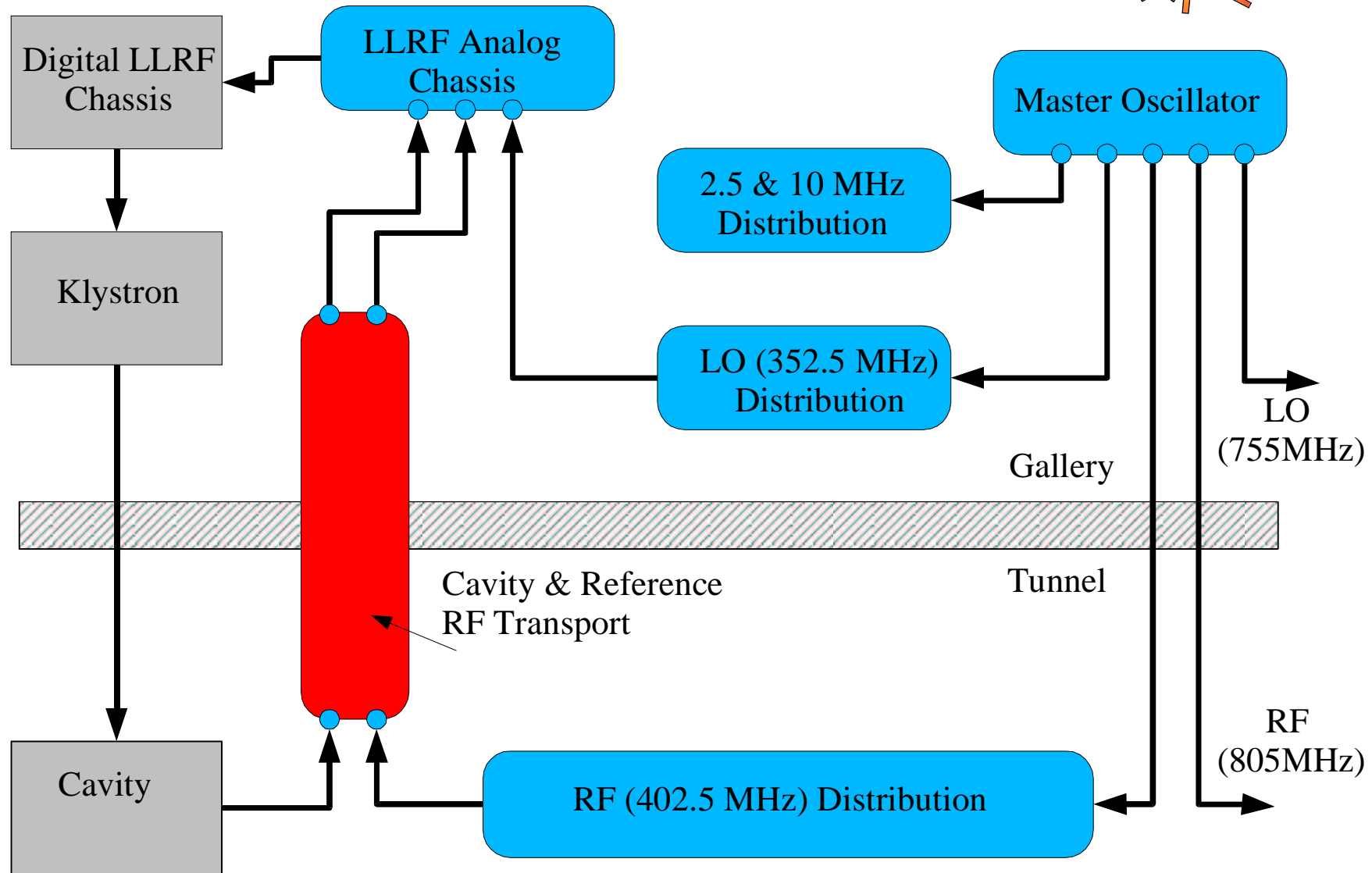
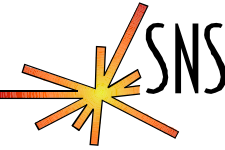
## Pressure Control System (3 of 3)



Dehydrator & 5 psi Pressurization Unit



# SNS LLRF Reference System



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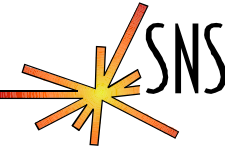


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# SNS LLRF Reference System

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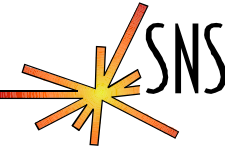
## Reference RF and Cavity RF Transport (1 of 3)

- Cavity RF and Reference RF signals Transported from Tunnel to RFC rack using heat treated phase matched 3/8" Heliax cables.
- Phase/Temperature coefficient is -4 to +3 PPM/C (very stable)
- Propagation Velocity =  $0.88 c$
- Wavelength = 65.6 cm @402.5 MHz



# SNS LLRF Reference System

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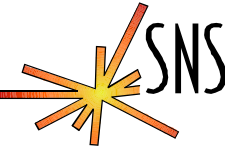
## Reference RF and Cavity RF Transport (2 of 3)

- Cable Lengths expected to be less than 120 feet (36.6 m) or 56 wavelengths
- Reference RF and Cavity RF cables will be routed through a 1" conduit in the klystron gallery to minimize cable length:
  - Reduce differential phase drift errors
  - Reduce control system feedback latency
  - Reduce temperature variations of cables



# SNS LLRF Reference System

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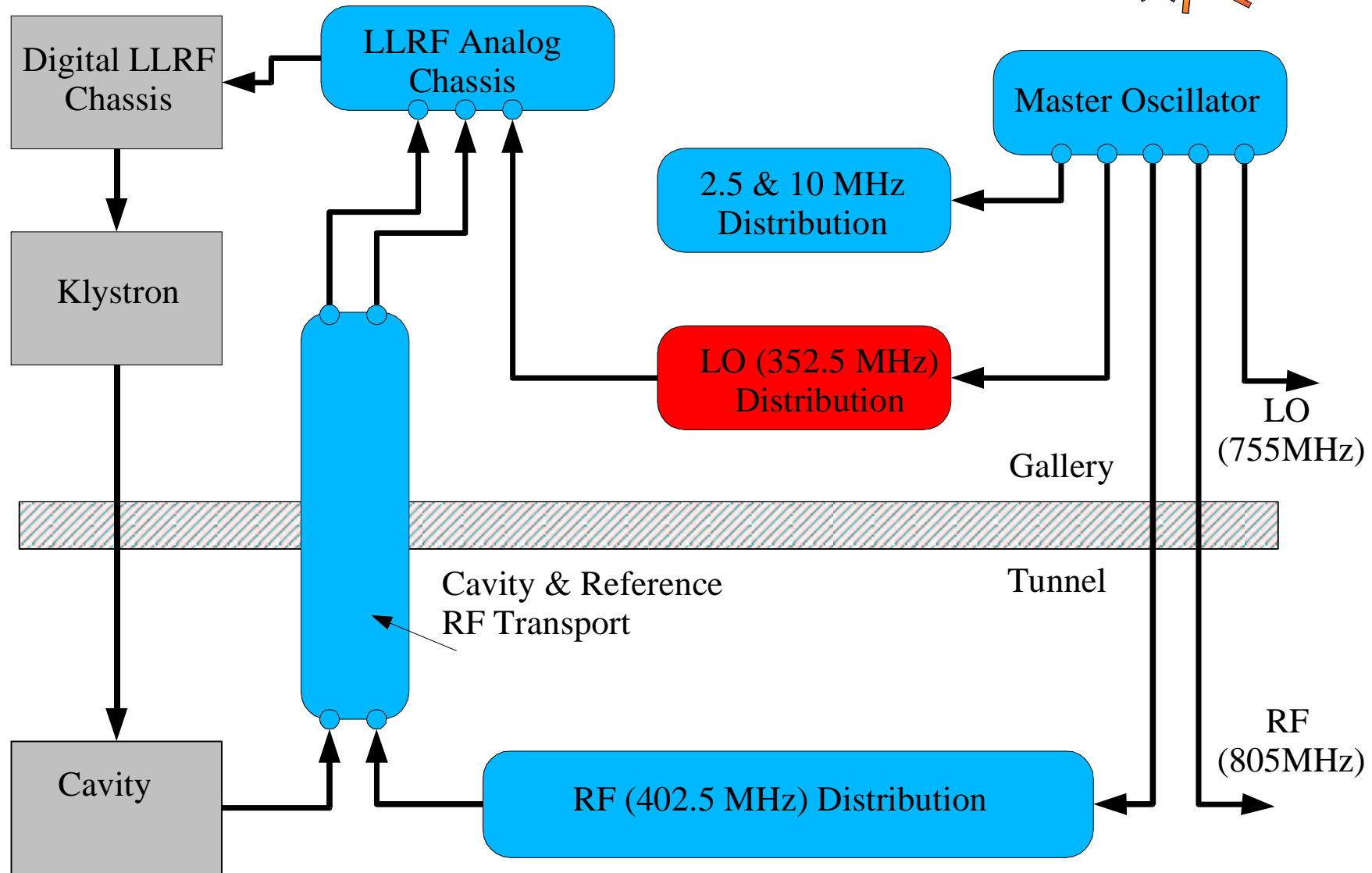
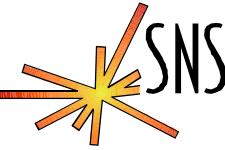


## Reference RF and Cavity RF Transport (3 of 3)

- Attenuation is 7.06 dB/100m, we should see less than 3 dB loss in our cables.
- Solid corrugated copper outer conductor provides excellent shielding ( > 90 dB isolation).
- Andrew Type N-male captivated connectors used, PE replacement dielectrics in Tunnel



# SNS LLRF Reference System



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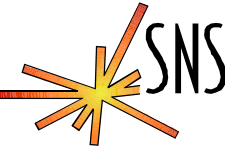


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# SNS LLRF Reference System

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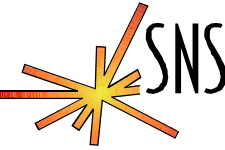
## Reference LO (352.5 MHz) Distribution (1 of 5)

- Power Amplifier
- Distribution
- Diagram



# SNS LLRF Reference System

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## Reference LO (352.5 MHz) Distribution (2 of 5)

Power Amplifier (same type as for RF 402.5 MHz)

- Rack mount chassis in Master Oscillator Rack
- Gain = 40 dB
- Noise Figure < 8.6 dB
- Typical Maximum Power Output = 50 Watts
- Minimum 1 dB Compression Point = 25 Watts



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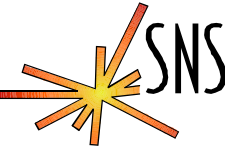


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# SNS LLRF Reference System

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## Reference LO (352.5 MHz) Distribution (3 of 5)

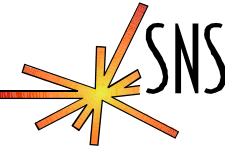
### Distribution

- Star type distribution
- LO phase drift OK (cancelled out in the down/up conversion process)
- 3/8" Heliax cable, all runs < 100 feet
- Type N-male captivated connectors



# SNS LLRF Reference System

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## Reference LO (352.5 MHz) Distribution (4 of 5)

### Distribution

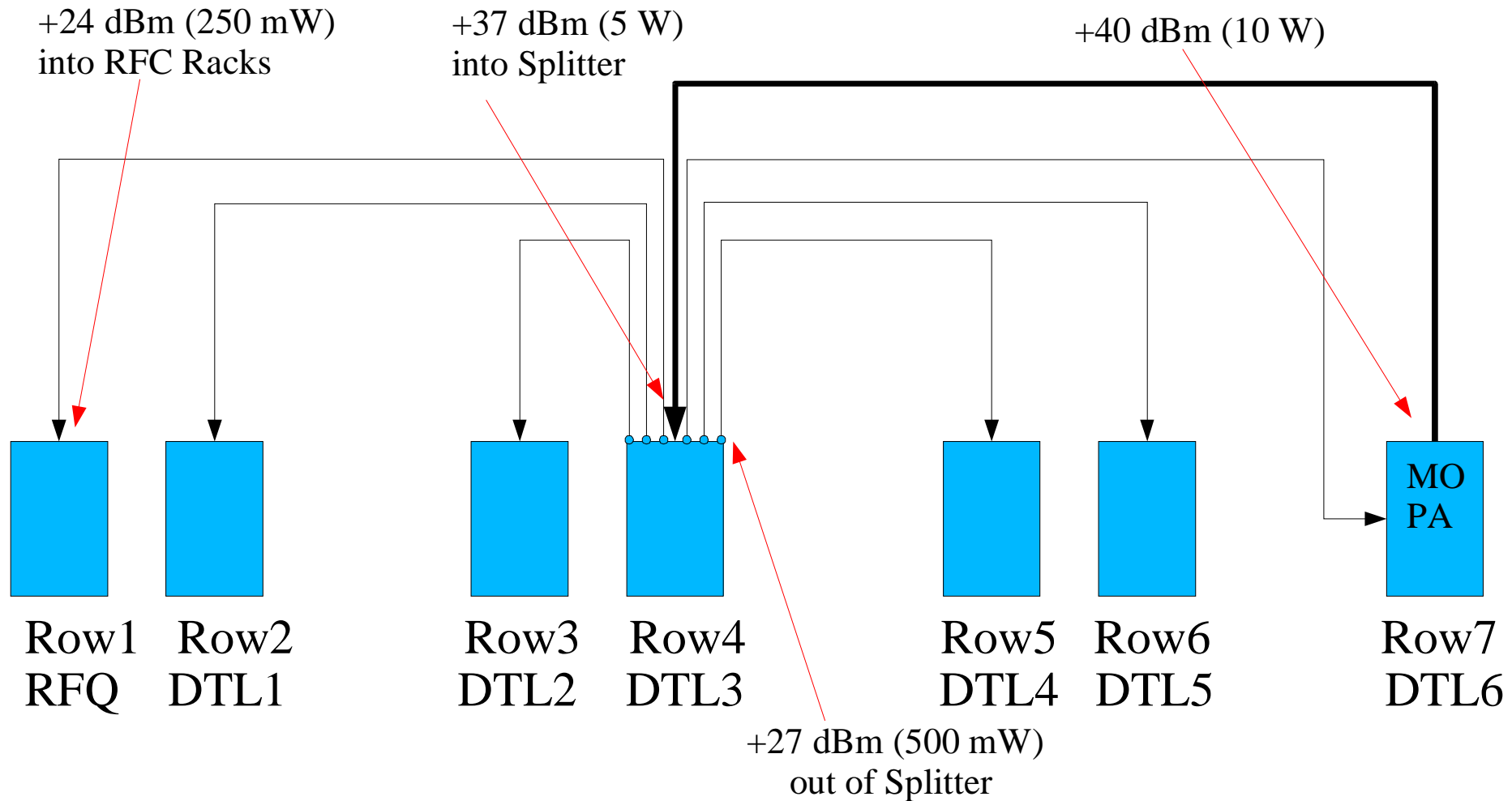
- Eight way power splitter in Row 4
- Isolation  $> 30$  dB
- Spare channel monitored via Epics
- All LO system components/signals accessible in racks



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## Reference LO (352.5 MHz) Distribution (5 of 5)



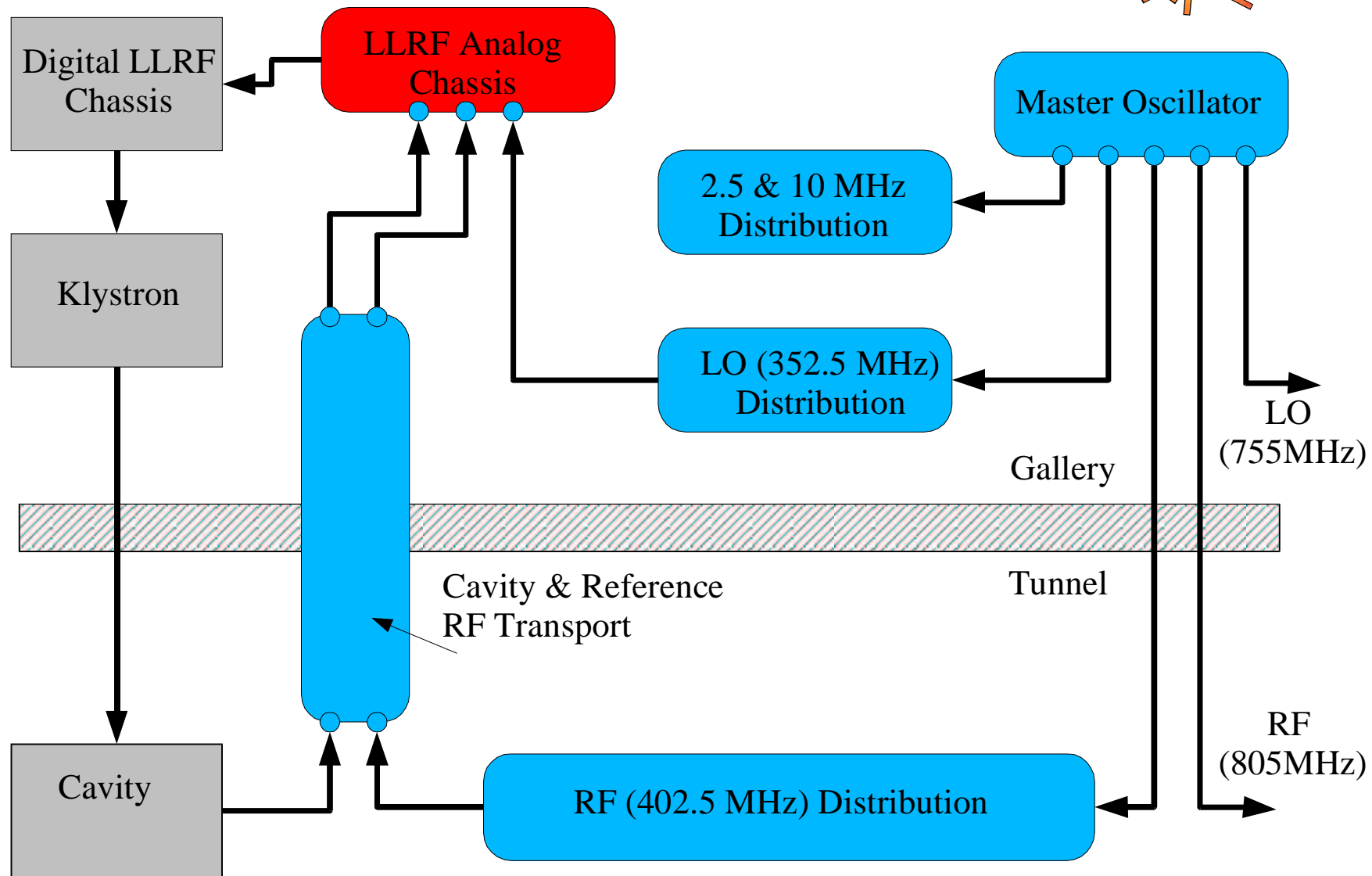
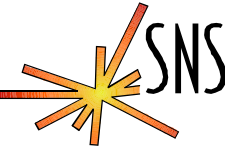
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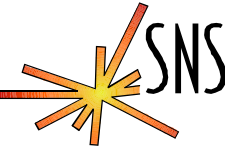


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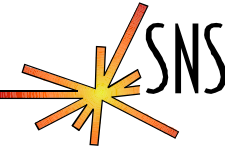
## LLRF Analog Chassis (1 of 3)

- Located in RFC racks
- Performs Down-conversion of Reference RF and Cavity RF signals (402.5 MHz) to IF signals (50 MHz)
- Distributes Forward RF and Reverse RF signals
- Prototype chassis now in use with RFQ



# SNS LLRF Reference System

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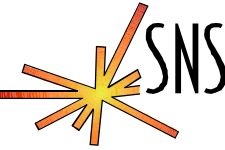


## LLRF Analog Chassis (2 of 3)

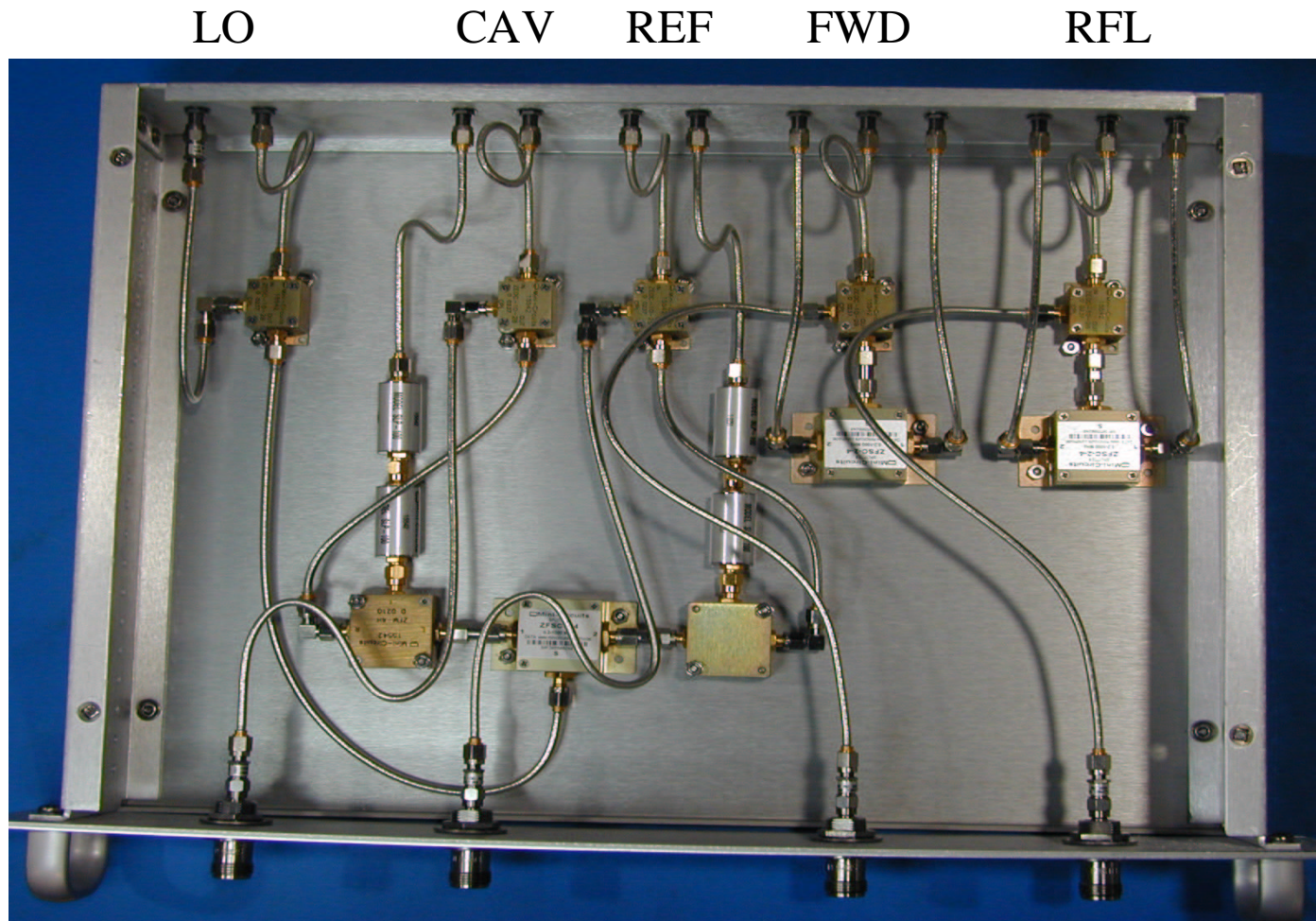
- All signals available in RFC racks
- Chassis will be Temperature Regulated (no thermal drifting of analog components)
- Uses MiniCircuits ZFM 4H level 17 double balanced mixers
- Hengjie Ma to perform additional mixer measurements



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## LLRF Analog Chassis (3 of 3)



Prototype  
Chassis

CAV

REF

FWD

RFL



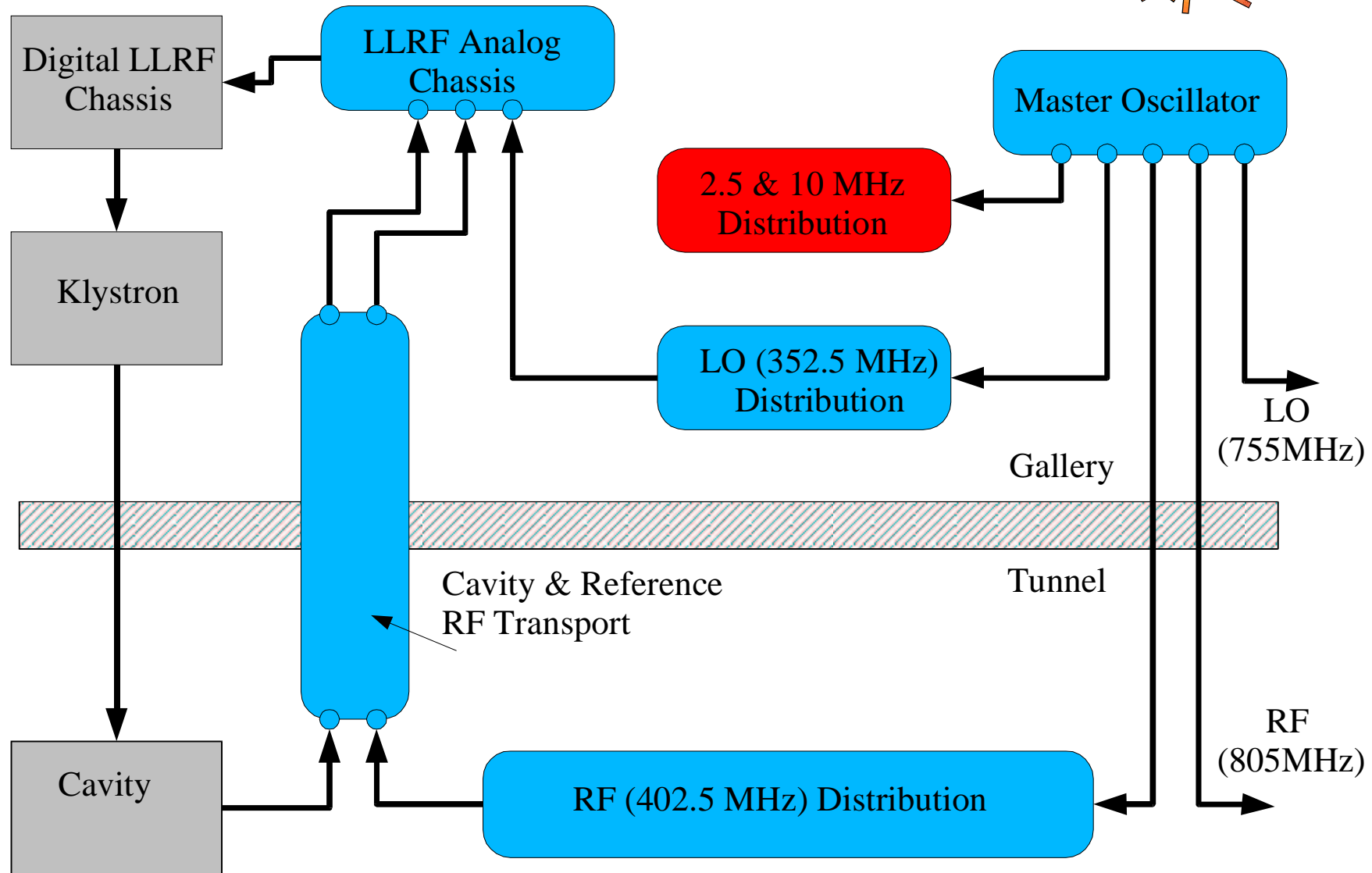
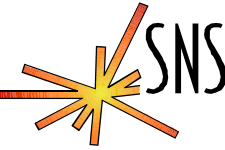
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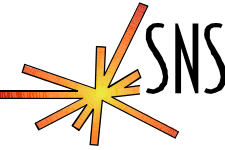


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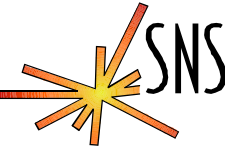
## 2.5 MHz and 10 MHz Distribution (1 of 1)

- 2.5 MHz and 10 MHz will be available in Gallery
- Need input from other groups



# SNS LLRF Reference System

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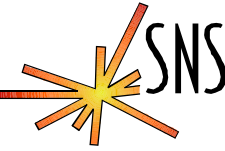
## Why We Think it Will Work

- Reference RF Distribution in Tunnel
- Radiation Resistance
- Reference RF and Cavity RF Transport



# SNS LLRF Reference System

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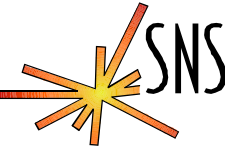
## Reference RF Distribution in Tunnel (1 of 3)

- Phase drift must be less than 0.1 degree between adjacent cavities
- Phase drift will occur via Temperature and Pressure drifts.



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## Reference RF Distribution in Tunnel (2 of 3)

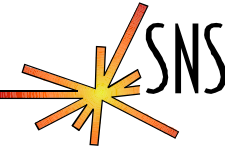
### Temperature

- Temperature can be regulated to  $\pm 0.1$  C
- Phase/Temp coefficient is 16.5 PPM/C for Copper Rigid line
- Cavity Spacing is 6 m.
- Temperature induced phase drift is therefore 0.00966 degrees between adjacent cavities



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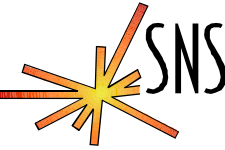
## Reference RF Distribution in Tunnel (3 of 3)

### Pressure

- Initial tests revealed a phase change of 0.02 degrees occurs during the dehydrator compressor cycle period for a 200 foot length of rigid line.



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## Radiation Resistance of Materials (1 of 3)

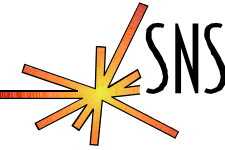
Material	Total Integrated Dose (MRad)
Teflon	0.1
Nylon	1
Polyethylene	100

- Front End/DTL: 2 Rad/hr, 40 year Total Integrated Dose = 0.4 MRad
- SCL near beamline: 60 Rad/hr, 40 year Total Integrated Dose = 12 MRad



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## Radiation Resistance of Materials (2 of 3)

Solid Polyethylene (PE) possesses excellent electrical properties

- Dielectric constant = 2.3 (compared to 2.1 for Teflon)
- Dielectric constant is flat vs. frequency
- Material is easily machined
- Heliax cables use low density PE foam as dielectric material



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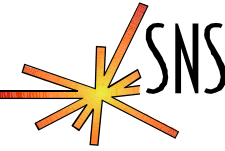


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## Radiation Resistance of Materials (3 of 3)

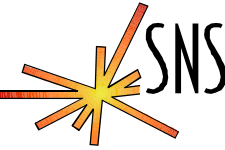
### Require Custom Made components for Tunnel

- Teflon Rigid Line components being replaced by Polyethylene parts (Connecticut Microwave Corporation)
- Teflon coaxial connector components being replaced with Polyethylene parts (Molex)
- Heat tape and RTD Temperature Sensors use Kapton
- Keep RF components out of tunnel where possible, replace Teflon with Polyethylene



# SNS LLRF Reference System

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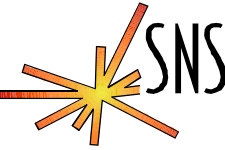


## Reference RF and Cavity RF Transport

- Temperature Data
- Differential Phase Drift Measurement



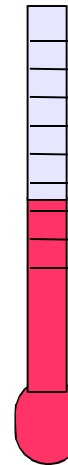
# SNS LLRF Reference System



## Temperature Data (1 of 2)

Device	Temperature
RFQ	24 C (75 F)
DTL, CCL	22-26 C (72 - 79 F)
SCL	??

Expected Temperatures



### Local Temperature Information

Location	Temperature	Period
Gallery	+/- 5 F	24 Hours
Chase	+/- 2 F	24 Hours
Tunnel	+/- 2.5 F	12 Months

### Global Temperature Information

Location	Beam On/Summer	Beam Off/Winter
Gallery	85 +/- 5 F	75 +/- 5 F
Tunnel	85 +/- 10 F	72 +/- 10 F



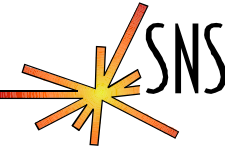
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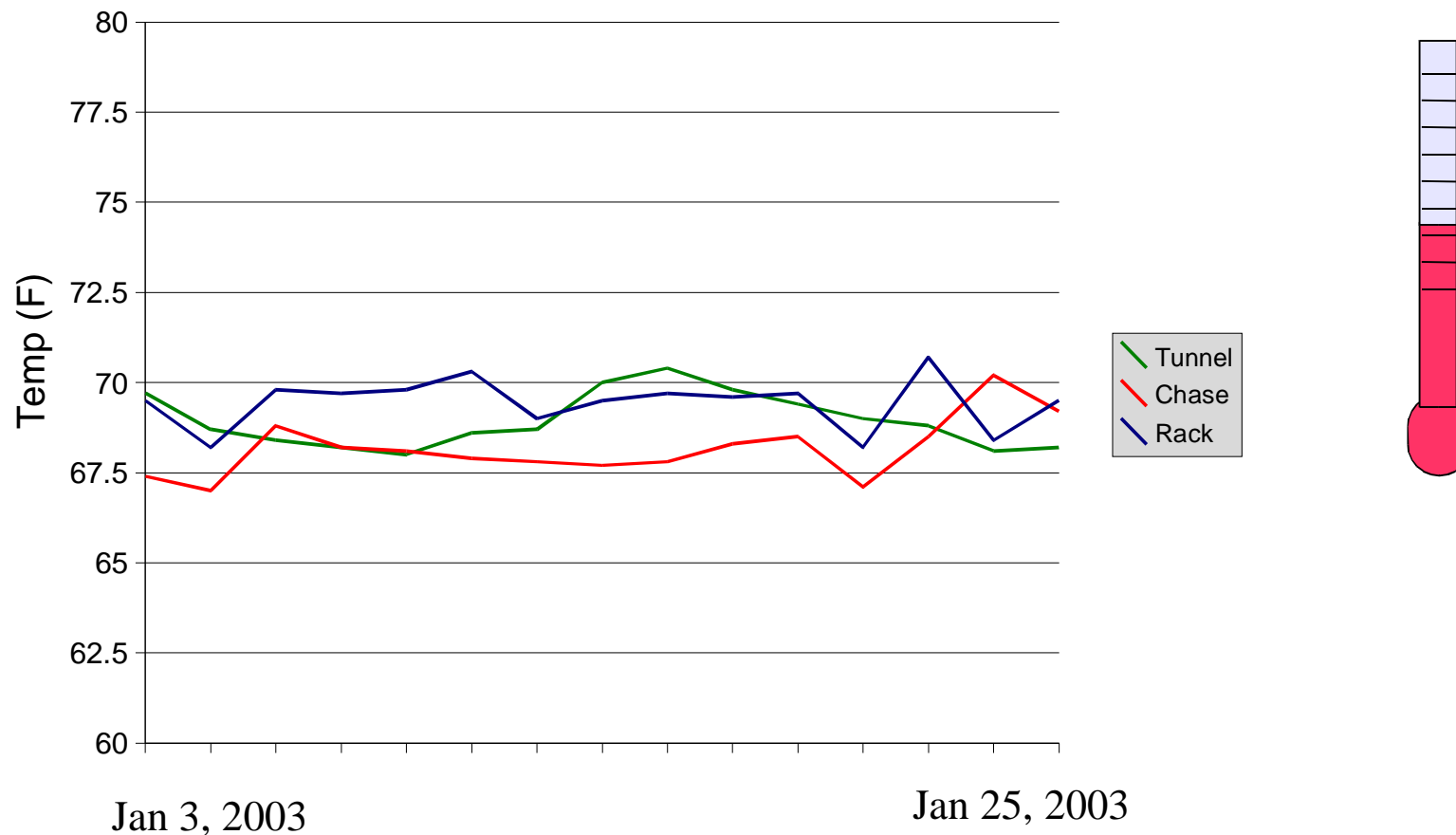
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# SNS LLRF Reference System

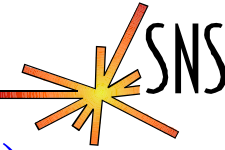


## Temperature Data (2 of 2)

Measured Tunnel, Chase, Rack Temperatures For DTL6

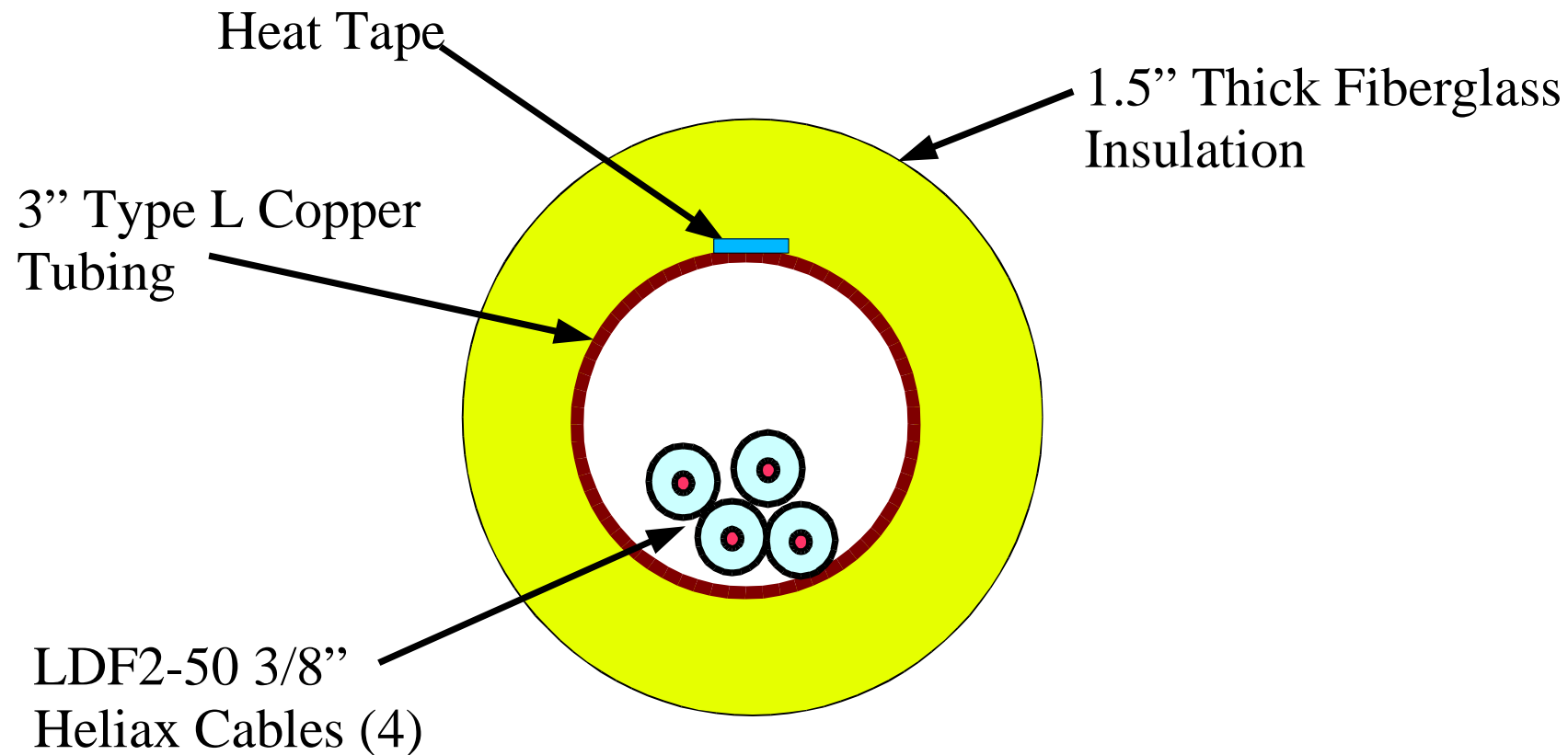


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## Differential Phase Drift Measurement (1 of 5)

Temperature Chamber Cross Section



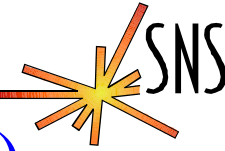
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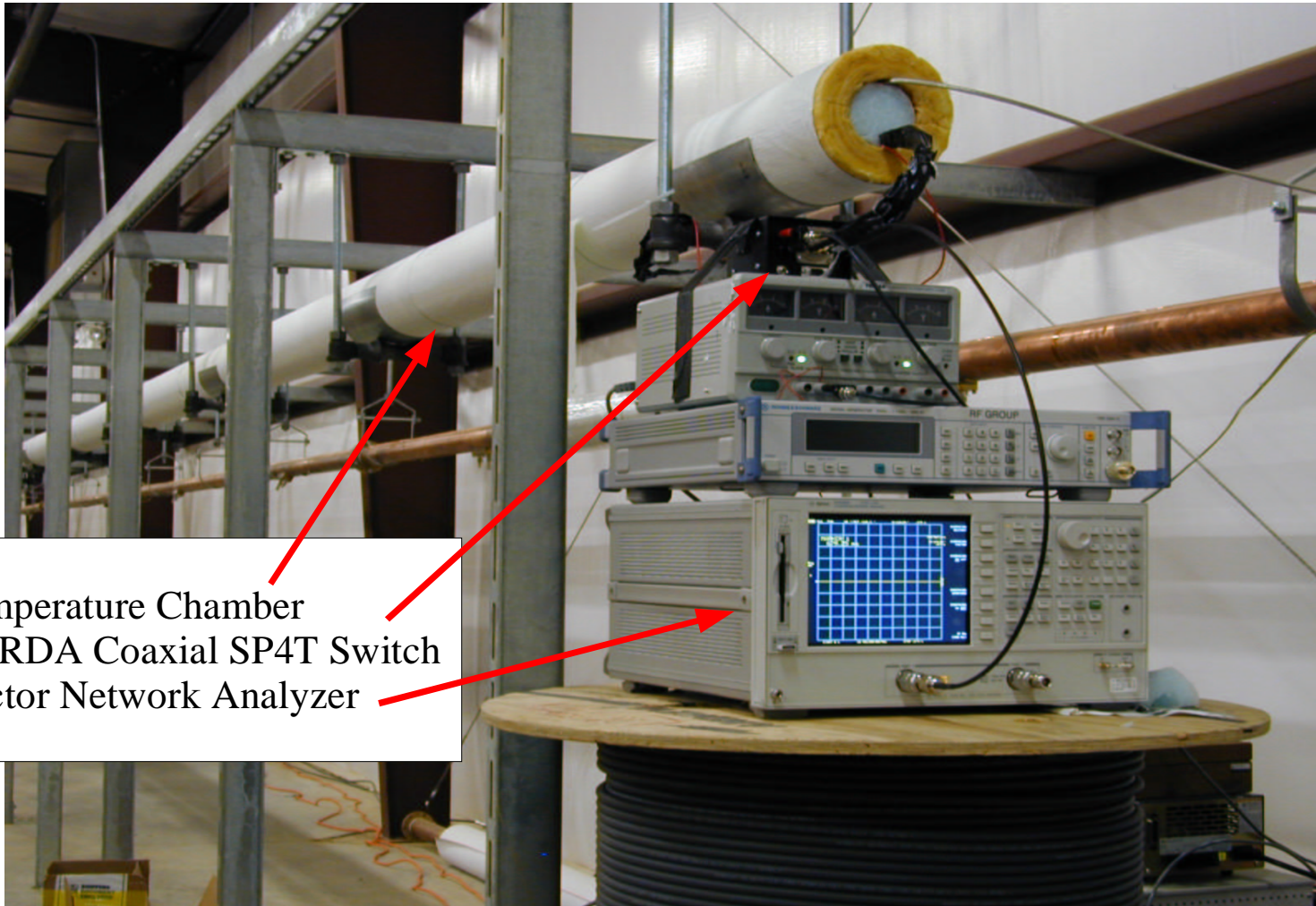
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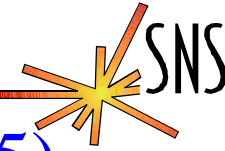
## Differential Phase Drift Measurement (2 of 5)



Temperature Chamber  
NARDA Coaxial SP4T Switch  
Vector Network Analyzer



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## Differential Phase Drift Measurement (3 of 5)

- 4 Cables, 402.5 MHz, length 251ns (66m or 217ft). Preliminary data, values in degrees.

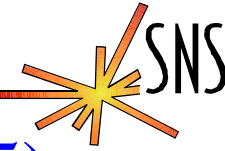
	#1	#2	#3	#4		
100F - 80F	2.20	2.85	3.26	2.71		
100F - 70F	3.14	3.98	4.45	3.76		
80F - 70F	0.92	1.13	1.19	1.05		

	#1 - #2	#1 - #3	#1 - #4	#2 - #3	#2 - #4	#3 - #4
100F - 80F	-0.65	-1.05	-0.51	-0.41	0.14	0.54
100F - 70F	-0.85	-1.32	-0.63	-0.47	0.22	0.69
80F - 70F	-0.21	-0.27	-0.12	-0.06	0.08	0.14



# SNS LLRF Reference System

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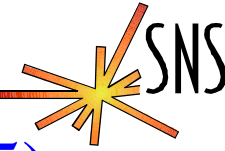
## Differential Phase Drift Measurement (4 of 5)

- Cable length in test was 251 ns vs. expected real cable length of less than 136 ns (84% longer than expected)
- Temperature difference in test much greater than measured data or expected temperatures in real machine
- Initial test cables were not phase matched, differential phase drift was lower on the better matched cables.



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## Differential Phase Drift Measurement (5 of 5)

- Continue Differential Phase Drift measurements
- Reduce cable lengths
- Reduce cable temperature fluctuations
- Phase match cables
- Cables to be sequentially pulled from same reel



Good



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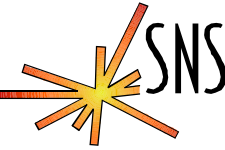


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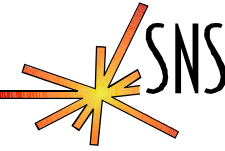
## 402.5 MHz Schedule (1 of 1)

- LO: end of February
- RF: mid March
- Entire system: early April



# SNS LLRF Reference System

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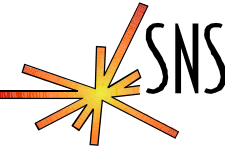


## Future Plans: Single Path (1 of 4)

- Baseline Design uses two parallel but completely separate analog component chains to bring Cavity and Reference signals from Tunnel to Digital Control System.
- Single Path uses a single analog component chain for both the Cavity and the Reference signals
- Single Path provides complete phase error cancellation in analog feedback path



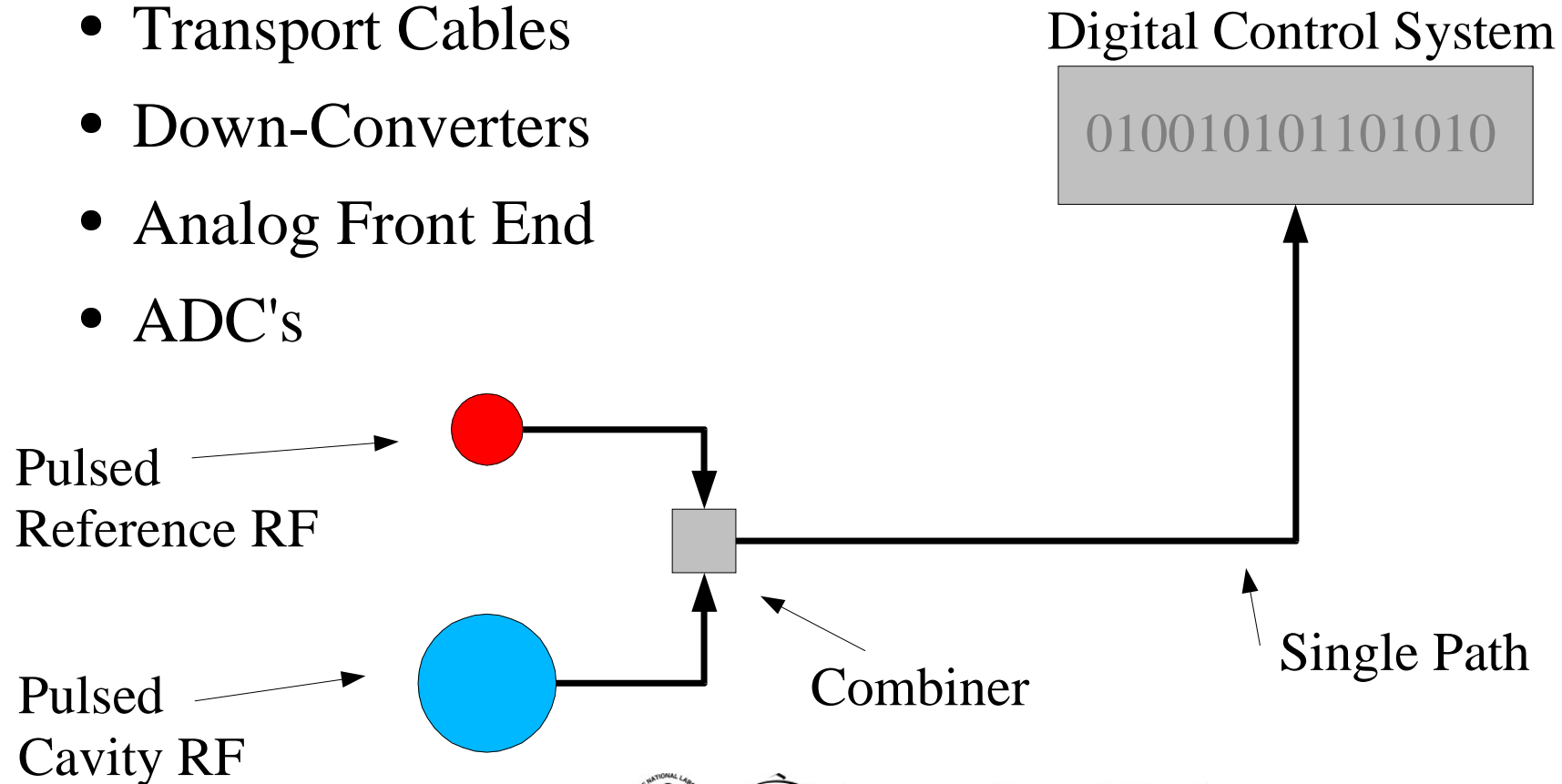
# SNS LLRF Reference System



## Future Plans: Single Path (2 of 4)

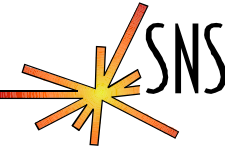
- Phase Drifts/Errors eliminated from:

- Transport Cables
- Down-Converters
- Analog Front End
- ADC's



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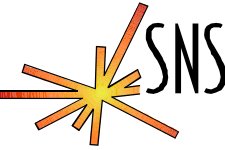
## Future Plans: Single Path (3 of 4)

- Single Path requires:
  - Software change in control system
  - Pulsed Reference RF signal
  - Combiner in tunnel for each Cavity/Reference signal pair



# SNS LLRF Reference System

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## Future Plans: Single Path (4 of 4)

Initial Testing shows:

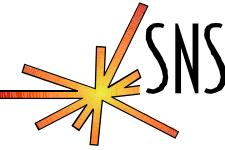
- 79 dB cavity to cavity isolation in 402.5 Mhz section (field amplitude crosstalk = 0.01 %)
- 95 dB isolation for Minicircuits Model SASWA-2-50DR solid state switch for pulsed Reference RF signal

 Very Good!



# SNS LLRF Reference System

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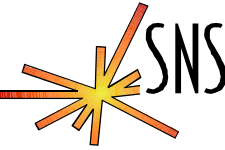


Thanks!

- Much thanks and appreciation to the following folks (and some I may have left out):
  - M. Champion, M. Crofford, T. Davidson, R. Fuja, Y. Kang, H. Ma, M. McCarthy, A. Regan, T. Rohlev, J. Stovall, D. Thomson



# SNS LLRF Reference System



## Coaxial Cable Properties

Cable	LDF2-50	LDF5-50A	LDF7-50A	MACX350
Size	3/8"	7/8"	1-5/8"	3-1/8"
Loss 400 MHz	7.06	2.49	1.43	0.65 est.
Loss 800 MHz	10.2	3.63	2.13	0.91 est.
(dB/100 m)				
Propagation Velocity	0.88 c	0.89 c	0.88 c	0.99 c
Phase/Temp	-4 to +3	+3 to+7	??	16.5
(PPM/C)				
AVG Power Rating	663 W	2.19 kW	4.52 kW	15 kW est.
(1 GHz)				

